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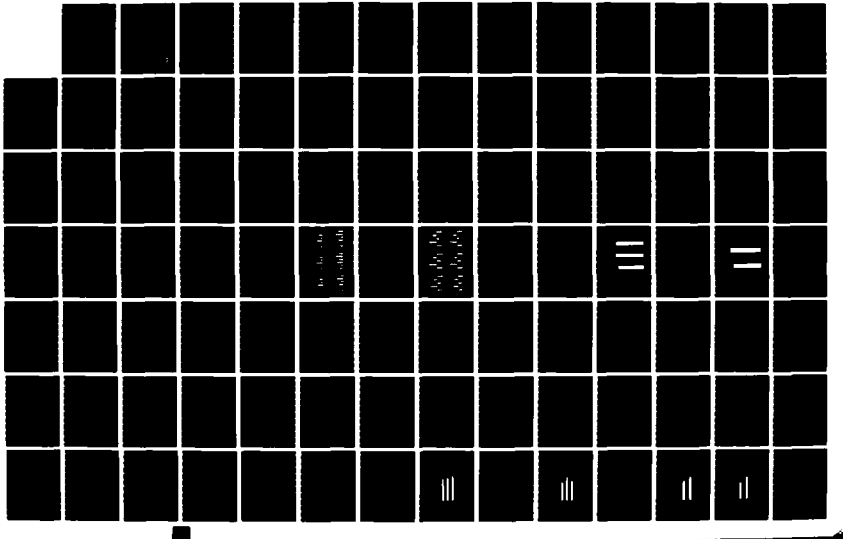

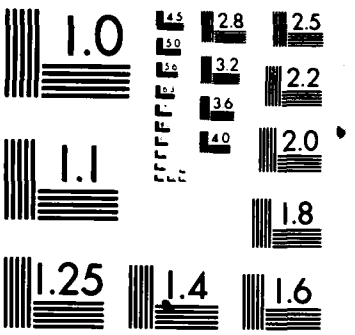

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A PSYCHOPHYSIOLOGICAL MAPPING OF COGNITIVE PROCESSES

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The purpose of these studies was to map the psychophysiological concomitants of cognitive processes. To this end, a modified Sternberg paradigm was used in which the trials were divided into three parts, each beginning with a stimulus. The first, or "cue," stimulus informed the subject as to the character of the following "memory set." In studies 1 and 2, the cue simply signified the number of letters in the memory set (1,3, or 5 in study 1; 2 or 6 in study 2). In study 3, the cue also indicated the character type of the letters: either English or Japanese, the latter essentially nonsense patterns for these subjects. The third, or "test," letter called for a response as to whether it was a member of the memory set. Physiological responses recorded were ERPs to the above stimuli and to task-irrelevant "probe" stimuli appearing in the interstimulus intervals, and in Studies 1 and 2, heart rate and blink parameters.

In study 1, in the interval preceding the memory set, where attentional demands varied with set size, probe ERP P1-N1 amplitude increased with set size. In the next interval,

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Block 19, Abstract
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where encoding and rehearsal demands were great, probe ERP N1-P1 amplitude declined with higher set sizes. The cue effect was interpreted in terms of the activation of a specific attentional system. The memory effect was viewed in the context of a limited capacity model. Blink rate also consistently slowed before each task stimulus. A striking set size effect was seen in the memory interval where the largest set was associated with a marked blink inhibition. This was seen as due to the additional time necessary to read in the larger set.

In study 2, probe stimuli were both visual and auditory so as to assess the specificity of the study 1 ERP effect. Also, a longer interstimulus interval (ISI) was added to evaluate the set size effect in the relative absence of the potentially overriding deceleration preceding each task stimulus. The heart rate results replicated the general patterns seen in study 1 and though the ISI increase yielded greater accelerative and decelerative swings, no new set size effects were produced. Blink data similarly reinforced the observations of study 1, in particular replicating the memory interval set size effect. The ERP data were enigmatic, reversing the relationship between amplitude and probe position seen in study 1, and lacking the set size effect. Effects were generally limited to the visual stimulus, however.

The third study examined the differences between left and right hemispheres of the brain in the anticipation of verbal (English character) and nonverbal (Japanese character) sets. Neither heart rate nor blink data were reduced. The cue stimulus indicated both the number of items comprising the set, and also, on half the trials, the linguistic nature of these items. Asymmetries of processing were seen as shifts in the lateral distribution of ERPs elicited by the task stimuli, as well as by shifts in the lateral distribution of probe ERPs evoked during the periods before and after the memory set.

The major findings were consistent with the notion that the left and right cerebral hemispheres are relatively more efficient in the encoding and retention of linguistic and nonlinguistic information, respectively, when they are primed to do so. Specifically, when the type of characters comprising the memory set was cued, English character sets were found to elicit a larger P2 than Japanese sets over the LH, while over the RH, the reverse pattern was found. When character type was uncued, no asymmetries in memory set ERP P2 amplitude were found. Evidence suggestive of an asymmetric engagement of retention processes was provided by the finding of a diminished N2-P3 response to RVF probe stimuli when these were engaged in processing English character memory sets, and a diminished N2-P3 response to LVF probe stimuli when subjects were processing Japanese sets.

These findings, coupled with those of study 1, suggest that variation in probe evoked potential amplitudes reflects not only the number, but also the type, of information processing resources demanded by a primary task. The ERP results of study 2 apparently contradict those of both study 1 and 3. Several specific procedural differences were suggested as reasons for these discrepancies.

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STUDY 1

EFFECTS OF INFORMATION PROCESSING DEMANDS ON HEART RATE, BLINK PARAMETERS, AND TASK AND NONTASK (PROBE) EVENT-RELATED POTENTIALS.

INTRODUCTION

The strategy by which one allocates his/her limited attentional resources under conditions of increasing load has received considerable attention in recent years (Simons and Houck, 1983; Schiffrin, 1976; Schneider and Schiffrin, 1977). One procedure used to examine the manner in which a task is processed as the load is increased is the so-called secondary task paradigm. This paradigm typically requires the simultaneous performance of two tasks, one designated as of primary importance and the other as secondary. With increases in primary task difficulty, concomitant decrements in the strength of responses emitted to, or elicited by, the secondary task stimuli are taken to indicate that some stage, modality, or code of information processing (Wickens, 1979, 1980, 1984) is common to both tasks.

Among primary tasks that have frequently been used in electrophysiological studies are those that involve visual target tracking or detection of shifts in target trajectory. Secondary task stimuli (usually brief tones or light flashes, requiring overt responses or silent counting) are presented at random times during the primary task with the amplitude of the P300 component of an EEG

response (viz., the event related potential or ERP) evoked by these secondary stimuli yielding a measure of the average attentional requirements of the primary task over its duration. Studies employing this procedure have generally found attenuated secondary task P300 amplitudes when the demands of the primary task were increased. Variables used to produce the increase include the complexity of the control dynamics (Kramer, Wickens, and Donchin, 1983), and the number of elements or control dimensions to be tracked (Isreal, Wickens, Chesney, and Donchin, 1980b; Isreal, Chesney, Wickens, and Donchin, 1980a).

Although manipulation of the cognitive demands of the task in these ways reliably produces such effects, variation in the response demands has not (Isreal et al., 1980a). This discrepancy has been interpreted to mean that P300 indexes the activation of processing resources, particularly those dedicated to stimulus recognition and classification (for a review, see Hillyard and Kutas, 1983), which are independent of those involved in response selection and execution (Kutas, McCarthy, and Donchin, 1977; Magliero, Bashore, Coles, and Donchin, 1984; McCarthy and Donchin, 1981). This result accords well with current conceptions of the human information processing system as consisting of a number of functionally independent processing resources (Navon and Gopher, 1979; Wickens, 1980, 1984).

The majority of studies applying evoked potential methods to the evaluation of the mental load imposed by a primary task have used this single physiological measure, viz., the P300. The logic of this approach is that P300 provides the most accurate picture of the perceptual/cognitive demands imposed by the primary task. But there are several reasons why the assumptions of this procedure should be

questioned as well as its methodological adequacy, as it is presently implemented.

The first difficulty arises from the fact that multiple resource theory, as expressed by Navon and Gopher (1979) and applied in the work of Isreal and others, provides no reliable means of specifying in advance the particular processing resources upon which a task demand may draw; for example, in the work of Isreal and colleagues, independence of resources drawn upon by primary and secondary tasks is inferred from the failure of added primary task demands to significantly modify secondary task P300 amplitudes. The existing dual task ERP approach, therefore, has been somewhat ad hoc in its statements about the predicted overlap in demands of primary and secondary tasks. This may be remedied, to an extent, by employing more simply structured tasks which make it possible to specify, in advance, the area of maximal competition between the primary and secondary tasks. A related advantage that accrues to employing tasks in which the resources demanded are reasonably identifiable, is that the number of alternative processing strategies available to the subject are limited. This ensures that a priori assumptions made about the resource requirements of the tasks are applicable for the vast majority of subjects and remain constant for the time over which the load is assessed.

Another difficulty that arises from the convention of using a single physiological measure, viz., P300, to index task demands is that it precludes the detection of changes in the activity of other processors to which changes in the activity of the processor giving rise to P300 may be secondary (Putnam and Roth, 1985). This suggests that the assessment of task demands is a multivariate problem,

requiring the measurement of changes in antecedent ERP components as well as in other response systems, e.g., heart rate (Bauer, Keen, and Mouton, 1983; Jennings and Hall, 1980; Walter and Porges, 1976; Wierville, 1979) and blink rate (Holland and Tarlow, 1972) and blink latency (Bauer, Strock, Goldstein, Stern, and Walrath, 1986; Goldstein, Walrath, Stern, and Strock, 1986; Stern, Walrath, and Goldstein, 1983). In terms of the multiple resource theories proposed by Navon and Gopher (1979) and by Wickens (1980, 1984), we would expect that other responses, in addition to P300, should vary with task demands and that alterations in the pattern of these responses could provide a more complete picture of the capacities or resources that are varied by demand changes in the system. The functional cerebral locus of maximal competition between the primary task and the ERP-eliciting stimuli might then be more precisely inferred from the particular ERP component or components whose amplitude indexes the demand level.

A third difficulty with the existing secondary task P300 procedure is the failure of some of its proponents (excepting Kramer, Wickens, and Donchin, 1985) to consider the transiency of some mental workloads. This is implicit in the procedure of averaging together P300 responses to stimuli randomly distributed throughout the primary task. It seems evident that the effects of variation in primary task difficulty are limited to moments immediately preceding (if difficulty level can be anticipated) or following the presentation of the primary task stimuli, or that the nature of the processing may change over the sampled period. But if ERPs are obtained by averaging responses that occurred at random points during the primary task, such transient events are likely to be lost.

A final difficulty with the secondary task P300 procedure is more practical than theoretical and relates to its inadequacy when used to assess primary task workload in environments outside the laboratory. It has been suggested (Isreal et al., 1980b), for example, that a major advantage of the secondary task P300 procedure, relative to those which require overt manual or vocal responses associated with the secondary tasks, is its unobtrusiveness. This is a criterion of considerable importance in the assessment of mental workload, viz., that the act of measurement should not disrupt the performance of the primary task whose demands are to be evaluated. There are many situations (outside of a laboratory), however, in which the introduction of a secondary task of any sort, even one as minimally obtrusive as that used to elicit a P300, might be considered inappropriate.

Thus, although information regarding the presence or absence of competition between primary and secondary tasks of various sorts may be critical in answering some questions about the structure of the human information processing system and in serving as an aid in the design of man-machine systems that minimize competition, the data provided thus far by the secondary task P300 procedure seem incomplete or inadequate. The present experiment was conducted for the purpose of seeking solutions to these problems.

To provide a task in which the resource demands are reasonably clear, we have adopted a discrete trial paradigm which, at different points in a trial, clearly requires the engagement of qualitatively different processing resources. It is a variation of Sternberg's (1966, 1975) memory scanning task in which each trial consists of a sequence of three stimuli. The first is the "cue" stimulus, a

numeral, which informs the subject of the number of items comprising the subsequent stimulus. In the period following the cue, there must be a pattern of preparatory activity whose characteristics, we assume, reflect the expected processing demands imposed by the subsequent stimulus. The second stimulus of the trial is a set of consonant letters (the "memory" stimulus), varying in number, that the subject is instructed to encode for later comparison. In the interval following this memory stimulus, there must be a loading of processing resources, particularly those dedicated to encoding and rehearsal, which are qualitatively different from those engaged during the cue interval. Finally, the third, or "test", stimulus is presented, which may or may not be a letter from the preceding memory set. Additional processes are invoked by this stimulus which differentiate the test period from the prior two.

This is a task in which the demands placed on separate cognitive processing resources can be varied, and relatively easily identified. The issue then becomes one of selecting the most appropriate dependent physiological measure. As noted previously, the secondary task P300 procedure, as conventionally implemented, fails to satisfy several requisite criteria (after Wickens, 1984) for a mental workload procedure, viz., unobtrusiveness, diagnosticity, and validity. In an attempt to satisfy the first of these criteria, i.e., unobtrusiveness, the existing procedure was revised such that ERPs were elicited not only by the task stimuli, but also by "probe" stimuli, stimuli of no instructed relevance to the concurrently performed task. The assumption underlying the use of this "background" probe ERP procedure is identical to that which supports the approach of Isreal, Kramer, Donchin, and colleagues; namely, that

a brain region is less responsive to an extraneous stimulus, and therefore emits an ERP component of smaller amplitude to it, when that region is already engaged by a task. Data which document the sensitivity of this procedure to changes in workload level have been provided by Papanicoulaou, Johnstone, and others (Johnstone, Galin, Fein, Yingling, and Marcus, 1984; Papanicoulaou and Johnstone, 1984).

With regard to the second criterion of workload assessment, diagnosticity, the present investigation enlarges on those conducted by Isreal, Kramer, and others, whose sole focus, until recently (Kramer and Sirevaag, 1985b), has been on the P300 and the resources whose activity it is thought to reflect. As described earlier, the relationship between physiological response and mental workload is a complex multivariate problem which suggests the use of a number of physiological measures. In the context of the proposed experimental design, we might expect that the interpretation of an increase in the amplitudes of early components of the probe ERP, when attentional demands are increased (as in the cue interval), would be simplified if this increase were accompanied by other, peripheral, signs of anticipation, e.g., decreases in heart rate, blink rate, and blink duration. The interpretation of a reduction in the amplitudes of middle latency components of the ERP, when encoding and rehearsal demands are increased (as in the memory interval), would derive similar benefit if this reduction were accompanied by peripheral signs of motivated inattention or environmental rejection (Lacey and Lacey, 1974), e.g., increased heart rate.

Finally, in accord with the third criterion of mental workload assessment, viz., validity, the points in the trial at which workload

was assessed by probe stimuli were varied systematically and sorted separately so that transient changes could be tracked.

METHOD

Subjects

Seventeen male Washington University students, aged 18-26 yrs, were paid for their participation in the experiment. All subjects were right-handed and had normal or corrected-to-normal vision.

Apparatus

Sessions were conducted with the subjects seated in a 2.3 m x 2.75 m, sound-attenuated, electrically-shielded room, isolated from the experimenter and equipment. Illumination was provided by two overhead incandescent lights located to either side and slightly behind the subject chair. Ambient light intensity was 0.8 candela.

Stimulus delivery and timing were controlled by an LSI 11/23 computer. The task-relevant stimuli were presented by activation of an alphanumeric display unit (IEE Inc., 1 x 20 Dot Matrix Display Module #3600-14-020) centered behind a 1.3 cm clear slit running horizontally along the length of a 1.9 m x 0.6 m black plastic sheet. The sheet was flexed along its length into a 120 degree circular arc and fixed to the surface of a table. The subject was seated within the concavity of this arc, with his eyes 1.5 m distant from it. A single axis joystick (left-right), with which the subject could indicate his response, was attached to the table near the subject's right hand.

The probe stimuli were produced by illumination of a 7 watt incandescent bulb (100ms, 15.05 cd/m**2) positioned on the inside back wall of an enclosed box, the front of which was a 34 cm x 34 cm translucent panel. This diffusing panel was centered 42 cm above the

central display.

Three measures of physiological activity were recorded: EEG, EOG, and EKG. Electroencephalographic (EEG) activity was recorded from chlorided Grass silver cup electrodes applied to two midline scalp sites, Fz and Pz (International 10-20 System, Jasper, 1958), and covered by gauze pads impregnated in collodion. Each of these electrodes was referenced to linked, chlorided, silver Grass clips attached to the earlobes. Electrooculographic (EOG) activity was recorded from Beckman miniature biopotential electrodes taped above and below the left eye. For the recording of the electrocardiogram (EKG), electrodes of this same type were positioned on the lateral aspects of the rib cage. The subject was grounded with a Beckman electrode taped to the center of his forehead. Inter-electrode impedances were kept below 5 Kilohms.

The EEG and EKG signals were amplified by Tektronix Model AM 502 differential amplifiers (EEG: gain = 10K, nominal bandpass = 0.1 to 1000 Hz; EKG: gain = 2K, AC bandpass = 0.1 to 1000 Hz) and the EOG, by a specially-constructed amplifier, gain = 1.5K, bandpass = DC to 1KHz. Each of these physiological signals, along with stimulus and response event markers, were stored in digital form (sampling rate = 200 Hz) on computer disk, for off-line analysis.

Stimuli

The cue stimulus was the numeral, "1", "3", or "5" (avg. luminance = 8.21 cd/m**2 approximate retinal angle subtended = 15' x 20' high) projected for 700 ms at the center of the LED display. The memory set and test stimuli were presented for the same duration and centered at the same location. The letters in the memory set were selected at random, without replacement, from a set of 18 consonant,

upper-case letters (excluding "Y", "W", and "V") and arranged in a stimulus series with three restrictions: in each sequence of 150 trials, the three set sizes occurred equally often, the test stimulus was a member of the memory set on one-half of the trials, and on such trials it occurred with equal frequency at each position in the memory set.

Procedure

Subjects were tested on 2 days (modal interval = 2 days) at approximately the same clock time. Each experimental day was divided into three trial blocks. The first was a 5 minute block consisting of 30 practice trials. This was followed by two 31 minute blocks consisting of 113 and 112 trials, separated by a 3-5 min rest period.

Each trial, as diagrammed in Figure 1.1, consisted of a cue stimulus, a memory set, and a test stimulus, presented at 5700 ms intervals (SOA). On 90% of the trials, a probe light was presented at one of nine temporal locations (1000, 1300, 1600, 2200, 2500, 2800, 3400, 3700, or 4000 ms after stimulus offset) in the interval following the cue stimulus and at one of these nine latencies in the interval following the memory set. On 10% of the trials (i.e., 45/450), the probe stimulus was omitted from either the cue or memory interval and inserted, instead, in the intertrial interval.

Subjects were instructed that the value of the cue stimulus, would indicate the number of letters that would appear in the memory set presented 5000 ms later. Five seconds after memory set offset, a test item was presented, to which subjects were instructed to make a speeded discriminative response with the right hand. For nine of the subjects, this meant that they were to move the joystick to the right if the test item was an element of the memory set (a "positive"

response), and to the left if it was not (a "negative" response). For the remaining eight subjects, this was reversed.

Subjects were told that the probe stimuli were irrelevant to the task. An instruction to maintain fixation on the LED display at all times was used to ensure this bias.

Insert Figure 1.1 about here

Data Reduction

Event-Related Potentials. The EEG and EOG signals were digitized on-line at a rate of 200 Hz and were digitally filtered off-line (0 dB at 40 Hz, -3 dB at 43 Hz, -6 dB at 55 Hz) prior to analysis. In order to exclude from analysis any ERPs that might be contaminated by eye movement, lead sway, or muscle artifacts, EEG epochs for stimuli on which the variability in either the EOG or EEG exceeded preset criteria were rejected. Remaining epochs of EEG from 100 ms preceding to 500 ms following stimulus onset were retained. For each subject, these data were combined into time-point averages, temporally locked to the stimuli. The averages were computed separately for Fz and Pz leads. For the "Task ERPs", i.e., those elicited by the cue, memory set, and test stimuli, the averages were further sorted by these task stimulus types and by set size. For the "Probe ERPs", the averages were subdivided by set size, interval (cue vs. memory), and their temporal position within the interval. Although there were actually 9 probe positions in each of the two intervals, these were condensed, for analysis, into sets of 3 probe positions in each interval, designated respectively, "early", "middle", and "late" (Figure 1.1). Probe ERPs elicited during the intertrial interval were discarded.

The number of epochs averaged to form each Task ERP was 48, but due to attrition by the criteria described above, the number which formed Probe ERPs ranged from 21 to 38. The temporal distribution of the EEG epochs comprising each of these ERPs was approximately rectangular both within and across the experimental sessions.

Six components were identified in each of the averaged ERPs. Task ERPs were characterized by a complex of 6 alternate positive- and negative-going waves occurring within latency ranges of 90-140, 140-190, 190-230, 230-280, 280-430, and 430-500 ms post-onset. The maximum or minimum voltage of the averaged ERP occurring within each of these windows was determined to be the amplitude, with respect to a 100 ms pre-stimulus baseline, of P1, N1, P2, N2, P3, and N3, respectively. Six components were identified in the probe ERPs as well. Here, peaks or troughs occurring within latency ranges of 100-160, 160-200, 200-260, 260-320, 320-375, and 375-450 ms were identified as P1, N1, P2, N2, P3, and N3, respectively.

Since Probe ERPs were typically superimposed on a changing baseline, their component amplitudes were converted to peak-to-peak values of successive peaks prior to analysis. This served to minimize the potentially confounding effect on Probe ERP component amplitudes of slowly developing waves, such as CNVs (for a review, see Rockstroh, Elbert, Birbaumer, and Lutzenberger, 1982), which might also be affected by the variables of interest. It was deemed unnecessary to convert the peak-to-baseline amplitudes of the task ERP components to peak-to-peak amplitudes, as there was no expectation that they would be similarly affected.

EKG and Performance. EKG and performance data were digitized on-line and later subjected to analysis. The digitized EKG signal was

converted to heart rate (HR), expressed as the number of whole and fractional beats per minute (bpm), occurring in each of eighteen 950 ms bins spanning the trial. It was averaged for trials of the same set size prior to analysis. Reaction times (RT), calculated from test stimulus onset, were segregated by stimulus match (positive vs. negative) and set size. The median RT within each trial category was taken as the measure of central tendency.

Blink latency, rate, and duration. A reduction program was applied to the digitized EOG signal which identified as blinks, those voltage deflections that met specified criteria (available on request) of polarity, amplitude, duration, and velocity. Blink onset times were expressed with respect to the onset of the preceding task stimulus. The number and 50% closure durations of blinks occurring within each of the eighteen 950 ms time bins spanning the trial was also calculated.

Singled out for special emphasis was the latency of the first blink to occur following onset of a task (non-probe) stimulus. Only those blinks preceding the first probe stimulus in the interval were accepted for this analysis. Median blink latencies were calculated from these data for each subject and sorted by task stimulus type (cue, memory, and test) and set size. For the analysis of blink rate and average closure duration, the data were sorted by interval (cue, memory, and test), bin (1-6), and set size.

RESULTS

Event-related Potentials

Results from the analysis of the task ERPs, those elicited by the cue, memory set, and test stimuli, and of the Probe ERPs, those elicited by the probe stimuli, will be presented separately. The

analytic procedure for both Task and Probe ERPs was a multivariate ANOVA (MANOVA). Univariate analyses are reported only when the test for that variable was significant in the overall MANOVA. The degrees of freedom for these analyses were adjusted, where appropriate, using the conservative Geisser-Greenhouse (1958) procedure. Adjusted df's are reported.

Task ERPs. Task ERP component amplitudes were significantly modified by stimulus type, set size, lead, and the interactions of lead with stimulus type and stimulus type with set size. As Figure 1.2 illustrates and the results reported in Table 1.1 confirm, the effects of stimulus type were evident in amplitudes of P1, N1, P2, and N2 which were greater in the memory set ERP than in either the cue or test ERPs. Stimulus type was reflected also in N3 amplitude, which was greater in the test stimulus ERP than in either the cue or memory set ERPs (Scheffe' test, $p<0.05$). Although electrode locus interacted with stimulus type in their joint effect on N1 and N3 component amplitudes, the effect was complex and not easily characterized (see Figures 1.2 and 1.3).

Insert Table 1.1 about here

Insert Figures 1.2 and 1.3 about here

Set size was also a significant factor influencing Task ERP components; the direction of the effect, however, depended on stimulus type. For example, as seen in Figure 1.2, the amplitudes of the P1, P3, and N3 components of the memory set ERP increased with

set size. In the test stimulus ERPs, in contrast, the amplitude of the P3 component showed a decline with increasing set size, as did N2 amplitude. These observations were borne out by the results of simple effects tests carried out for each task stimulus separately: CUE--Manova $F(12,54)=0.96$, $p>0.5$; MEMORY SET--Manova $F(12,54)=2.91$, $p<0.005$; P1: $F(1.9,30.4)=3.38$, $p<0.05$; P3: $F(1.8,30.0)=4.17$, $p<0.03$; N3: $F(1.9,29.5)=5.15$, $p<0.02$; TEST--Manova $F(12,54)=2.94$, $p<0.01$; N2: $F(1.7,27.6)=4.28$, $p<0.03$; P3: $F(1.5,24.8)=11.55$, $p<0.001$).

The only other significant overall effect on task ERP component amplitudes was electrode locus. Univariate analyses revealed that the amplitudes of P1 and P3 differed as a function of locus, the amplitude at Pz significantly exceeding that at Fz. The amplitude of the N3 component was also distinguished by recording derivation but here Fz amplitude was significantly greater than Pz amplitude.

Probe ERPs. Due to the size of the combined Fz and Pz data sets and the limitations of computer memory, separate analyses of the Fz and Pz Probe ERP data were required. The results of the analysis of Probe ERP component amplitudes at Pz are illustrated in Figures 1.4 and 1.5. These results will be presented first.

Insert Figures 1.4 and 1.5 about here

A number of tests were performed to assess the direct and interaction effects of set size on probe ERP component amplitudes for the Pz lead placement. The only set size effect was a three way interaction of interval, probe position, and set size (Manova $F(24.0,193.1)=1.77$, $p<0.02$) involving the P1-N1 ($F(3.4,51.2)=2.93$, $p<0.04$) and N1-P2 components

($F(3.1, 47.1)=5.32, p<0.01$). Post hoc analyses revealed that the set size effect was restricted to probe positions surrounding the memory set, i.e., the late probe position in the cue interval and the early probe position in the memory interval. The effect was also in opposite directions in the two intervals and, further, involved different components. Specifically, a test of the simple effects of set size indicated that the amplitude of the earliest measured component of the Probe ERP, P1-N1, was positively related to set size at the late probe position in the cue interval (Manova $F(12.0, 50.0)=2.93, p<0.05$); P1-N1: $F(1.6, 23.8)=4.04, p<0.04$), whereas the amplitude of an intermediate latency component, N1-P2, was negatively related to set size at the early probe position in the memory interval (Manova $F(12.0, 50.0)=3.12, p<0.01$; N1-P2: $F(1.6, 24.3)=7.90, p<0.004$). Set size did not affect Probe ERP component amplitudes at any of the other probe positions in either interval.

The only significant effect involving the Fz probe ERPs was an increase in P1-N1 amplitude as a function of probe position (POSITION--Manova $F(10, 52)=5.50$, $p<.0001$; P1-N1: $F(1.7, 25.2)=8.66$, $p<0.01$). This effect was mirrored in the Pz data, though it involved the N1-P2 component as well (Manova $F(12.0, 50.0)=3.50, p<0.001$; P1-N1: $F(1.9, 28.8)=4.97, p<0.02$; N1-P2: $F(1.4, 21.5)=7.07, p<0.01$).

Contingent Negative Variation (CNV)

To ascertain if the observed changes in Probe ERP peak-to-peak amplitudes were confounded by similar changes in the background EEG occurring just prior to probe stimulus onset, an analysis of the average baseline voltage of the Probe ERPs (expressed as the difference between it and the average baseline voltage of the

preceding Task stimulus ERP) was carried out. The results of an analysis of the Pz data showed that such concern was unwarranted, as this measure of CNV amplitude was not affected by set size, probe position, interval, or their interactions. Average CNV amplitude at Fz, however, was modified by the interactive effects of interval and probe position (Manova $F(12.0, 50.0)=2.73, p<0.01$; CNV: $F(1.6, 24.5)=8.31, p<0.01$). This effect was shown in a trend toward decreasing negativity over probe positions in the cue interval and increasing negativity, over probe positions, in the memory interval.

Heart Rate

As noted previously, each of the three task intervals in a trial was divided into six bins commencing, respectively, with the onset of the cue, memory set, or test stimulus. Absolute heart rate was calculated for each of the six bins of each interval. These data are displayed along the top three panels of Figure 1.6. A 3 (task interval) by 6 (time bins) by 3 (set size) ANOVA was performed on the HR data with all variables within.

Insert Figure 1.6 about here

Whereas HR exhibited a decelerative trend in the cue interval, it was mainly accelerative in the memory and test intervals. The significant time bin (pooled across intervals) effect ($F(1.6, 25.2)=25.20$, $p<0.0001$) reflects the average trend toward acceleration. The time course of the bin effect differed over the cue, memory, and test intervals. The initial effect is either nil or decelerative. This is followed by an accelerative phase of varying proportion and ends in a deceleration as the next stimulus is due.

The significant time bin by interval interaction ($F(3.18, 50.93)=40.76$, $p<0.0001$) suggests that these components are not represented in equal proportion in the three intervals.

Of greater pertinence to the present investigation is the postulated effect of set size on these patterns of HR change. It is evident from an inspection of the top panel of Figure 1.6 that set size had reliable effects, although these varied with time bin and interval (SET SIZE x INTERVAL: $F(2.5, 39.8)=5.02$, $p<0.01$; SET SIZE x BIN: $F(3.3, 53.1)=$ 30, $p<0.0005$; SET SIZE x INTERVAL x BIN: $F(4.9, 79.2)=6.61$, $p<0.0001$). To examine the time course of the set size effect across the trial, its simple effects were tested for each combination of bin and interval. Bins in which the set size effect was found to be statistically significant, i.e., $p<0.05$, are designated by arrows in the figure.

Blink Rate

The statistical model used for the analysis of blink rate was identical to that used for the analysis of heart rate.

The blink rate pattern during a trial showed alternating limbs of gradual deceleration and rapid acceleration. As can be seen in the blink rate response function displayed across the bottom three panels of Figure 1.6, the decelerative phases were associated with the imminence of task relevant events: the cue, memory set, and test stimuli. The significant bin effect ($F(1.9, 29.9)=36.2$, $p<0.0001$) reflects this trend.

Average blink rate differed across intervals ($X(cue)=15.6$, $X(memory)=17.1$, $X(test)=20.6$) ($F(1.4, 22.2)=19.37$, $p<0.0001$), and set sizes ($X(one)=16.7$, $X(three)=17.8$, $X(five)=18.82$) ($F(1.7, 26.8)=14.05$, $p<0.001$). The interpretation of these effects is qualified by the

participation of these variables in statistically significant first and second order interactions (SET SIZE x INTERVAL: $F(2.3, 36.3)=3.42$, $p<0.04$; SET SIZE x BIN: $F(5.1, 82.4)=10.65$, $p<0.0001$; INTERVAL x BIN: $F(4.4, 69.9)=5.28$, $p<0.001$; SET SIZE x INTERVAL x BIN: $F(4.4, 71.2)=12.71$, $p<0.0001$). Bins in which the set size variable was found to significantly modify blink rate, by simple effects test, are designated by arrows in Figure 1.6.

Blink Latency

Blink latency data were subjected to a 3 (task stimulus type) by 3 (set size) ANOVA. As can be seen in Figure 1.7, blinks occurred earlier (Scheffe' test, $p<0.05$) following the cue stimulus ($X=783.9$ ms) than following either the memory set ($X=905.1$ ms) or test ($X=873.5$ ms) stimuli (STIMULUS TYPE: $F(1.4, 23.1)=8.27$, $p<0.01$). Blink latency also increased with set size ($F(1.5, 23.9)=23.61$, $p<0.0001$), but the set size effect was a function of stimulus type (STIMULUS TYPE x SET SIZE: $F(2.1, 33.3)=9.13$, $p<0.0006$). Simple effects tests indicate that set size affected the latency of those blinks following the memory set only ($F(1.5, 24.9)=21.36$, $p<0.0001$).

Insert Figure 1.7 about here

Blink Duration

The average closure duration of blinks for each interval and bin is shown in Figure 1.8. The results of a three way ANOVA of these data indicate that blink duration declined over bins ($F(2.0, 17.9)=37.04$, $p<0.0001$), but increased over intervals ($X(cue)=138.2$ ms, $X(memory)=147.8$ ms, $X(test)=156.7$ ms) ($F(1.5, 13.1)=19.7$, $p<0.001$). No other effects, including set size or

interactions with set size, were significant.

Insert Figure 1.8 about here

Reaction Time

Performance by subjects was virtually flawless; error trials constituted 2.7% of the total, on the average. Such trials have been excluded from the present analysis.

Reaction time data (Figure 1.9) were submitted to a 2 way ANOVA in which the factors were set size and stimulus match. In this analysis, both the set size and stimulus match effects were significant ($F(1.5, 24.6)=64.70$, $p<0.0001$ and $F(1, 16)=32.21$, $p<0.0001$, respectively). The set size effect was reflected in a mean increase in RT per item scanned of 40 ms for matched items, and a mean increase of 42 ms for mismatched items. With respect to the stimulus match effect, judgments of mismatch took 103.8 ms longer, on the average, than judgments of match.

Insert Figure 1.9 about here

DISCUSSION

In the present study, event-related potentials elicited by task irrelevant probe stimuli were examined under conditions in which attentional and encoding/rehearsal demands were independently varied. In accord with the stated hypotheses, the elicitation of probe ERPs against these different backgrounds resulted in quite different relationships between set size and the amplitudes of early probe ERP components. Increasing set size produced enhanced probe ERP P1-N1

component amplitudes at the late probe position in the cue interval, but attenuated probe ERP N1-P2 amplitudes at the early probe position in the memory interval. These differences in the component reflecting the set size effect and the direction of the effect, depending on whether the ERP-eliciting probe stimulus preceded or followed memory set presentation, reinforce the contention that the changes mirror the activity of different processing resources.

The claim by others, that probe ERP component modulation, instead of indexing processing activity, may reflect "noncognitive influences on the brain's electrical activity" (Isreal et al., 1980b), is not supported by these data. Restricting ourselves to the cue interval, the set size effect did not have the diffuse topography associated with the operation of a global noncognitive process, such as arousal, in that the effect was limited to the Pz lead derivation. Also challenging the involvement of global noncognitive processes in this interval was the finding that the set size effect was not evident in measures of cardiac and slow cortical potential activity. Taken together, these data suggest the mobilization of a selective attentional system initiated by the cue stimulus, the graded activation of which was manifested in the positive relationship of set size to P1-N1 (at Pz) amplitude at the late probe position. It should be acknowledged, nevertheless, that the positive ERP amplitude/set size relationship found in this interval is not predicted by a limited capacity model, the model underlying the use of the probe stimulus method. One possibility is that selective attentional (sensory priming) processes are invoked when task and probe stimuli are in the same modality. This admittedly ad hoc hypothesis can be tested by use of non-visual probes.

That set size, in the cue interval, loaded processing resources that were distinct from those engaged in the memory interval, is indicated as well by the other physiological measures. Clearly, the decline in blink rate and duration over bins in the cue interval, coupled with the increase in probe ERP P1-N1 amplitude over probe positions, is consistent with the growth of an attentional set (cf., Naatanen, 1982) as presentation of the memory set becomes imminent. The significant decelerative trend in heart rate across the cue interval supports this interpretation and is consistent with the development of a preparatory set (Walter and Porges, 1976) or set for "stimulus intake" (cf. Lacey and Lacey, 1974). Recall, however, that set size, unlike for probe ERPs, had no modulating effect on the deceleration. Although congruent with some previous research (Jennings and Hall, 1980), the failure of anticipated cognitive load to influence heart rate is not in apparent accord with other reports (e.g., Walter and Porges, 1976). Although concordant with the present results, the range of load manipulated in the Jennings study did not extend low enough nor was it broad enough to have discriminated set size effects had such been present. On the other hand, in the Walter experiment, in which set size was apparently effective, the authors themselves pointed out the possible artifactual nature of the effect. The issue therefore remained unresolved by those two studies. The present data support Jennings' conclusion. Further, the near identity of heart rates in all set size conditions of the cue interval argues strongly against attributing the absence of a set size effect to insensitivity of the heart rate measure. Taken literally, the results indicate that the depression in heart rate as well as in blink rate and duration, signal the expectancy of a significant stimulus but not

the degree of anticipated cognitive work to be dictated by that stimulus.

Set size was shown to have quite different effects when patterns of physiological response were examined in the memory interval. As might be anticipated (cf., Goldstein et al., 1986), blink rate generally declined over bins in a manner similar to that occurring in the cue interval. For trials with a set size of five, however, blink rate was significantly depressed in the first bin and increased from the first to the second bin before declining. Consistent with the finding that blinks are inhibited during perceptual activity (Bauer et al., 1986), the initial depression suggests that the 5-item set took longer to read into memory than either of the smaller sets. This is supported by the prolonged latency to the first blink following the larger memory sets. Although it is tempting to view the subsequent elevated rate in the 5-item condition as compensatory for the initial inhibition, the enhanced rate was prolonged over too many bins to make this interpretation attractive. A reasonable alternative would be that it reflects enhanced effort directed toward the rehearsal of the larger set. The relative heart rate depression during this period for the 5-item set can be construed to support this position. Accordingly, rehearsal, which involves the consolidation of information, might be associated with a heart rate reduction, much as is the preparation for and initial encoding of environmental information. This is consistent with the view espoused by Jennings et al. (Jennings, Averill, Opton, and Lazarus, 1970) but only if we interpret rehearsal as a factor that increases the intensity of attention. The latter qualification is, of course, critical and its acceptance suggests at least a refinement of the

position advocated by Lacey and Lacey (1974); that is, continued repetition of material to which the subject has been exposed, without an attempt to manipulate it or integrate it with other stored material, is of a class of events closer to stimulus intake than to internal cognitive elaboration (in the Laceys' terms), and as such would be be associated with a deceleration. Blink rate differs, according to this breakdown, depending on whether information is either anticipated, is being read in, or is being rehearsed. The first two processes seem to be associated with an inhibition and the latter, with a relative acceleration. Although blink inhibition in the former two categories might be attributed to the visual nature of the task stimulus, previous research (Bauer et al., 1986) contradicts this common sense assumption.

With regard to the memory interval probe ERPs, a set size effect on N1-P2 amplitude was found 1-2 seconds after the memory stimulus was presented and presumably encoded, but not at other times. This can be viewed as consistent with the above analysis if we invoke once again the rehearsal process. That is, at the latency of the first memory probe, which occurred, on the average, 100 ms into the third bin, a functionally independent processing resource, influenced by set size, can be identified (recall that in this bin both heart rate and blink rate were exhibiting the set size effect). Unlike the positive effect of set size on the late cue interval probe response, the processing of this early memory interval probe stimulus is inversely related to task difficulty, as a limited capacity model would hold (and contradicting an arousal model; Eason, Harter and White, 1969). This would occur if the structures devoted to an early stage (but not to later stages) of rehearsal of the memory set (cf.,

Chapman, McCrary, Bragdon, and Chapman, 1979; Chapman, McCrary, and Chapman, 1981) exerted inhibitory effects on the processor giving rise to N1-P2 in direct proportion to their level of activity. By bin 4, this process seemed to be undergoing some transition (discussed below) and response to the probe ERP presented at this point and the next position no longer responded to set size.

The set size effects in memory interval blink rate and heart rate, described above, were superimposed on changing baselines, the former descending, the latter, ascending. The cardiac acceleration observed across the memory interval follows a pattern noted in several reports. Acceleration, in an analogous period in Jennings and Hall's (1980) study, was attributed to rehearsal, a view that is diametrically opposed to that presented above. It is not clear why the effects of rehearsal would increase in strength, as Jennings suggested, as the memory set becomes more remote in time; the opposite, it would seem, would be more likely. And yet, the set size effect in heart rate and the rearrangement of set size conditions in blink rate in the last two or three bins of the memory interval, do suggest the introduction of a different process. Unfortunately, the brief interstimulus interval may have created conditions where preparatory deceleration truncated the set size effect by overriding the full extent of the accelerative waves (cf., the dominance of deceleration over acceleration in Lacey and Lacey, 1971). Unmasking this effect by increasing the ITI may help clarify this issue.

The source of the early heart rate and blink rate effects in the test interval seems clear. The positive relationship of set size to these variables in the early bins can be readily attributed to time differences in the comparison process (i.e., memory scanning,

comparing) which is clearly evident, as well, in the RT differences (cf., Sternberg, 1966, 1975). These differences in the comparison process were not demonstrated in blink latency, however, which one would think to be a very robust indicator under those conditions. Perhaps the additional noise introduced by the programming of the response and its execution were sufficient to render the set size effect insignificant ($p=0.0956$); Bauer et al. (1986) have demonstrated the significance of response processes in altering blink latency which makes this possibility reasonable.

Two other aspects of the data are worthy of note. Many experiments (e.g., Adam and Collins, 1978; Andreassi and Jusczak, 1984; Ford, Roth, Mohs, Hopkins, and Kopell, 1979; Gomer, Spicuzza, and O'Donnell, 1976), including this one, have documented reductions in the amplitude of the P3 elicited by a test stimulus as a function of the number of items to which this stimulus was to be compared. Although a number of hypothetical constructs have been invoked to explain this effect (Pritchard, 1981), one that appears to account best for the reduction in P3 is an increase in subjective uncertainty as a positive function of the difficulty of the comparison (Jennings and Hall, 1980). Since, in other contexts, P3 amplitude has been shown to be inversely related to measures of certainty, or "subjective probability" (Donchin, 1981), reductions in P3 amplitude with increasing set size are to be expected.

The effects of set size and response type (match/mismatch), on RT found here, also agree with many previous reports (Sternberg, 1966, 1975). The joint findings of a positive relationship between RT and set size, and of parallel RT-set size functions for match and mismatch responses, have been attributed to the operation of a

comparison process, wherein the memory set is scanned exhaustively on match, as well as on mismatch, trials. The finding of significantly longer reaction times on mismatch than match trials is suggestive of greater uncertainty in the emission of a mismatch response (Ratcliff, 1985).

In summary, it appears that probe evoked potentials, especially when used in combination with other physiological measures, can provide substantially more information about primary task workload than the conventional secondary task P300 procedure, and with fewer difficulties. Taken together, the present results attest to the efficacy of a multidimensional approach to the study of mental workload and to the importance of accounting for the transiency of workload effects.

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TABLE 1

F-Ratios for Effects on Task ERP Component Amplitudes

	Multivariate		Univariate											
			P1		N1		P2		N2		P3		N3	
Source	df	F	df	F	df	F	df	F	df	F	df	F	df	F
LEAD	6/11	16.9*	1/16	16.3*	1/16	0.76	1/16	0.18	1/16	4.34	1/16	40.13*	1/16	82.94*
STIMULUS	12/54	7.58*	1.7/27.6	4.94*	1.8/30.1	3.57*	1.8/29.9	3.89*	1.9/31	4.38*	1.8/28.8	2.66	1.5/24.8	12.21*
SETSIZE	12/54	2.57*	1.5/23.6	0.53	1.6/25	0.75	1.3/21.3	0.06	1.3/21.3	0.67	1.7/27.5	6.32*	1.5/24.3	1.55
LEAD X STIMULUS	12/54	2.58*	1.7/27.5	1.87	1.8/29.6	11.2*	2/31.9	0.23	1.5.23.6	3.14	1.6/25.1	2.75	1.7/26.6	4.86*
STIMULUS X SETSIZE	24/207	3.28*	3/48.3	3.27*	2.3/37	0.78	2.4/38.6	2.41	2.9/46.2	4.23*	2.4/38.4	9.25*	3.24/51.8	5.42
LEAD X SETSIZE	12/54	1.8	------	----	-----	-----	------	-----	-----	----	-----	----	-----	----
LEAD X SETSIZE X STIMULUS	24/207	1.44	------	----	-----	-----	------	-----	-----	----	-----	----	-----	----

*p < .05

FIGURE CAPTIONS

Figure 1.1 Diagram of trial format giving examples and the onset and offset latencies (in seconds from the start of the trial) of task relevant events. Probe positions are indicated by arrows along the time axis.

Figure 1.2 Amplitudes of P1, N1, P2, N2, P3, and N3 elicited by the cue, memory, and test stimuli, as a function of recording lead and set size.

Figure 1.3 Group-averaged ERPs elicited by cue, memory, and test stimuli, as a function of recording lead and set size. Polarity = positive up. For precise estimates of ERP component amplitudes corrected for intersubject variability in component latencies, refer to Figure 1.2.

Figure 1.4 Amplitude differences between P1-N1, N1-P2, P2-N2, N2-P3, and P3-N3 components at Pz elicited by probe stimuli, as a function of interval, probe position, and set size.

Figure 1.5 Group-averaged ERPs at Pz elicited by probe stimuli, sorted by interval, probe position, and set size. Polarity = positive up. For precise estimates of ERP component amplitudes corrected for intersubject variability in component latencies, refer to Figure 1.4.

Figure 1.6 Top panel: Heart rate (in bpm) plotted as a function of interval, bin, and set size. Bottom panel: Blink rate (blinks/min) plotted as a function of interval, bin, and set size.

Figure 1.7 Latency of the first blink following task stimulus onset (in ms) plotted as a function of task stimulus type and set size.

Figure 1.8 Blink duration (in ms) plotted as a function of interval and bin.

Figure 1.9 Reaction time (in ms) plotted as a function of stimulus correspondence (i.e., positive vs. negative) and set size.

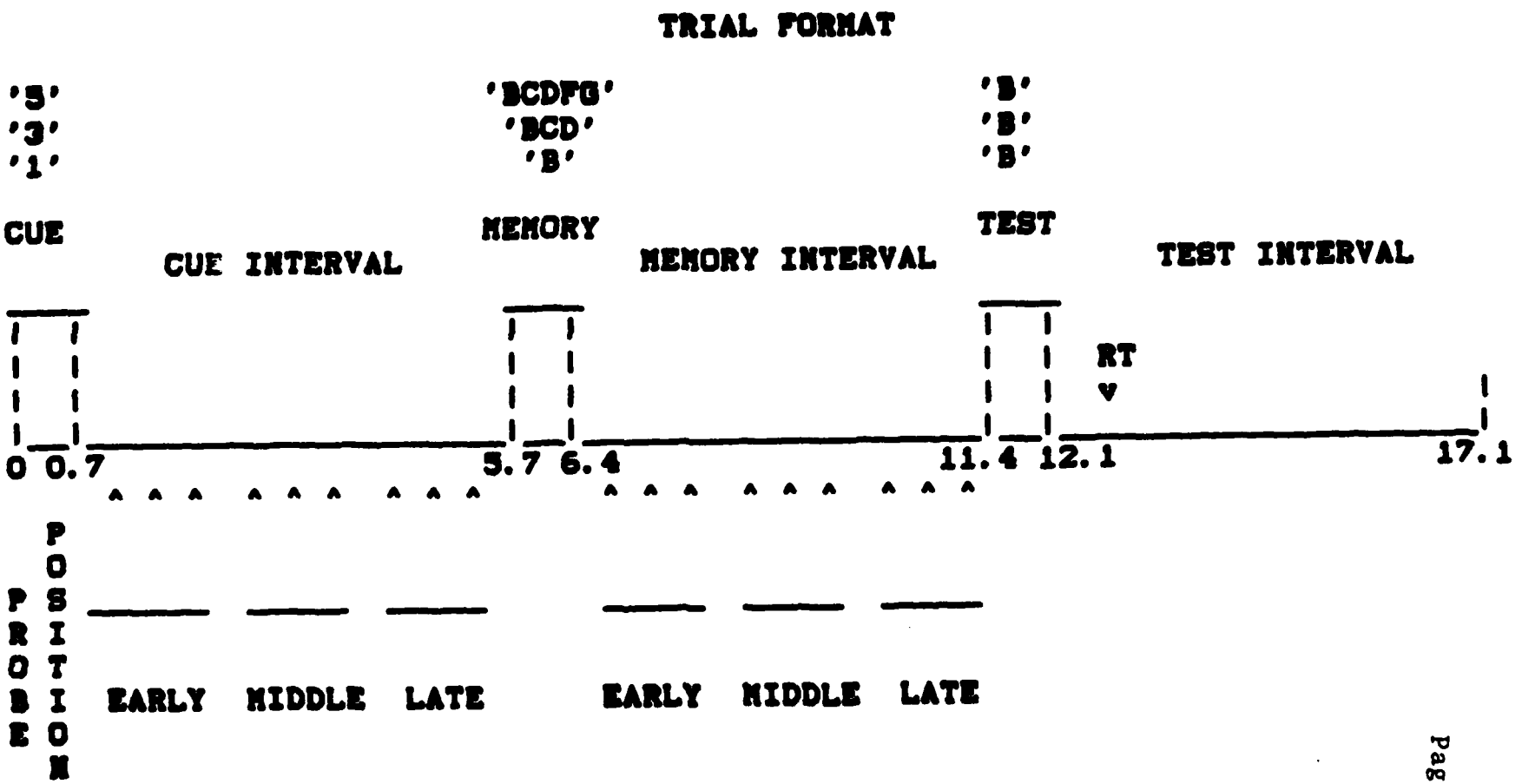
TRIAL FORMAT
'5'
'3'
'1'
'BCDFG'
'BCD'
'B'
'B'
'B'
'B'
CUE
MEMORY
TEST
CUE INTERVAL
MEMORY INTERVAL
TEST INTERVAL
RT
0
0.7
5.7
6.4
11.4
12.1
17.1
PROBE POSITION
EARLY
MIDDLE
LATE
EARLY
MIDDLE
LATE

Figure 1.1

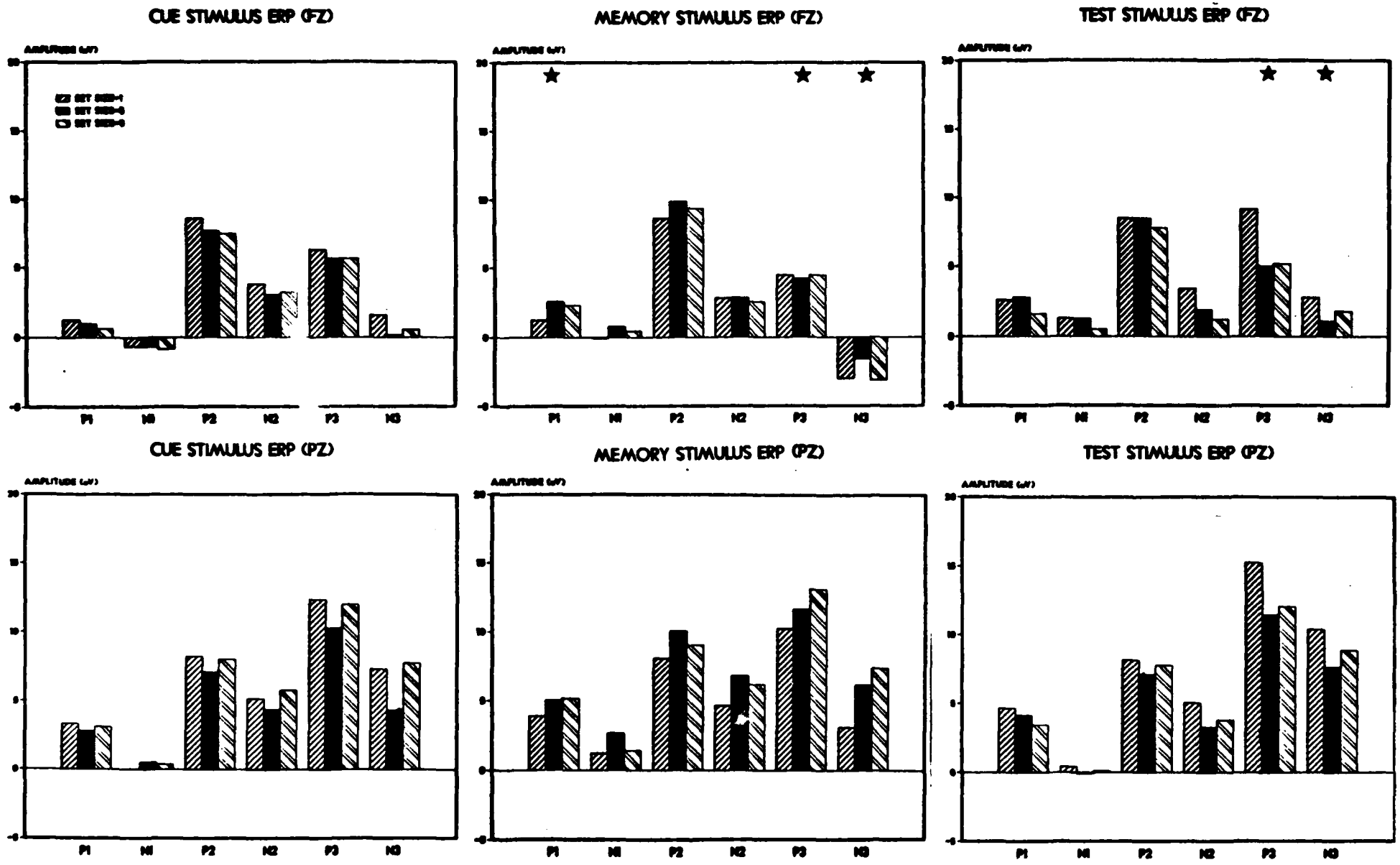
CUE STIMULUS ERP (FZ)
MEMORY STIMULUS ERP (FZ)
TEST STIMULUS ERP (FZ)
CUE STIMULUS ERP (PZ)
MEMORY STIMULUS ERP (PZ)
TEST STIMULUS ERP (PZ)
P1
N1
P2
N2
P3
N3

Figure 1.2

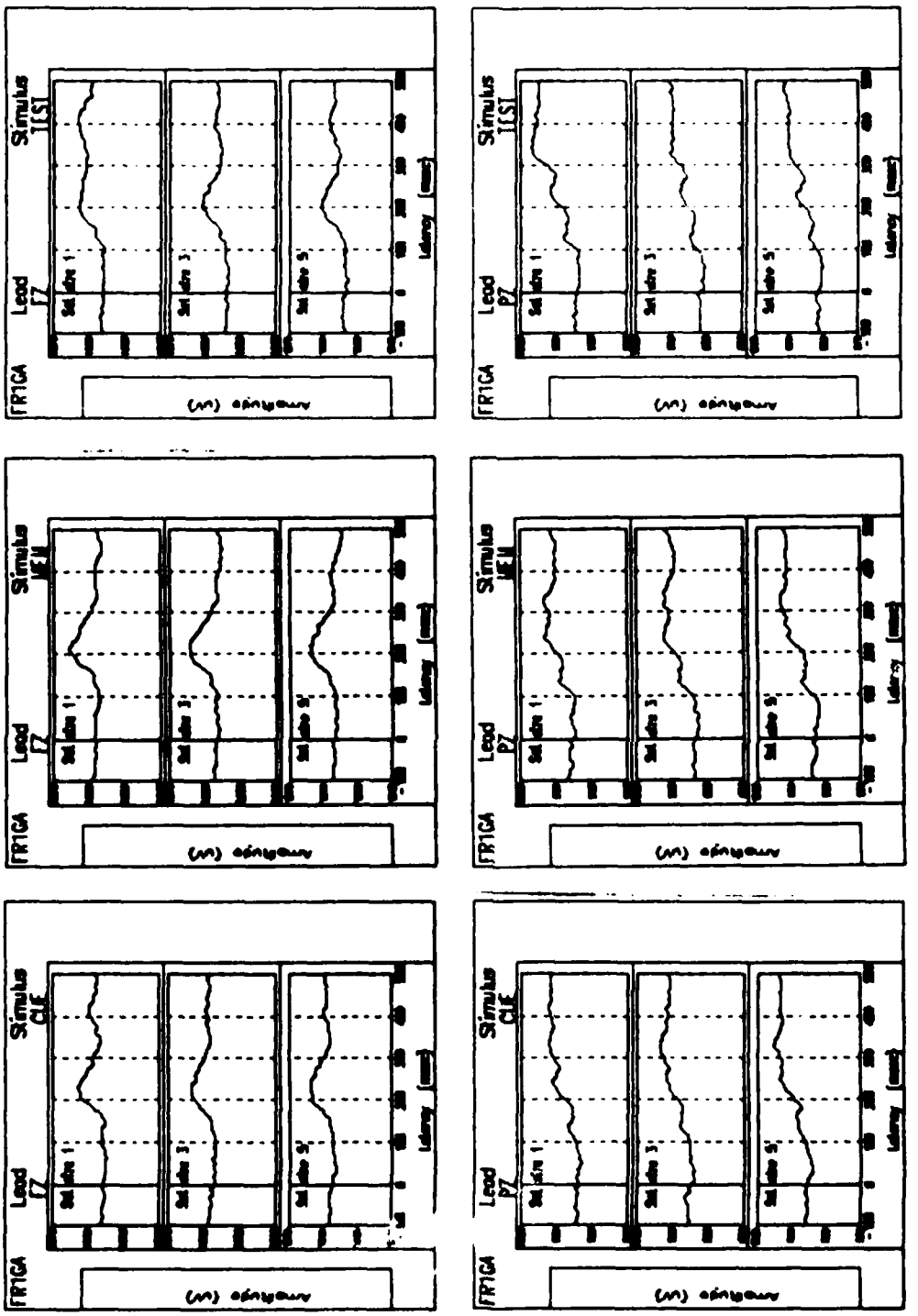

Figure 1.3

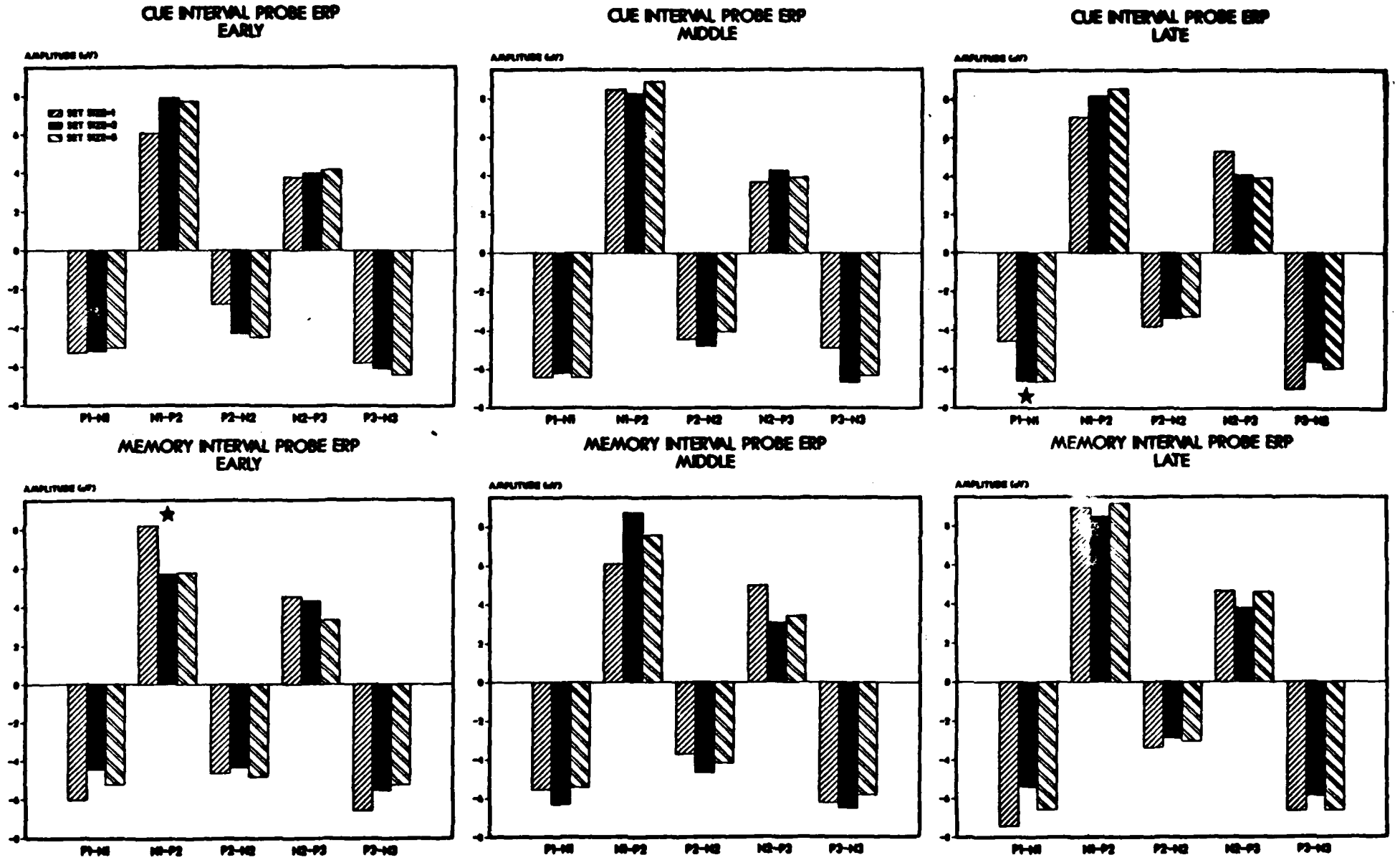
CUE INTERVAL PROBE ERP
EARLY
CUE INTERVAL PROBE ERP
MIDDLE
CUE INTERVAL PROBE ERP
LATE
MEMORY INTERVAL PROBE ERP
EARLY
MEMORY INTERVAL PROBE ERP
MIDDLE
MEMORY INTERVAL PROBE ERP
LATE

Figure 1.4

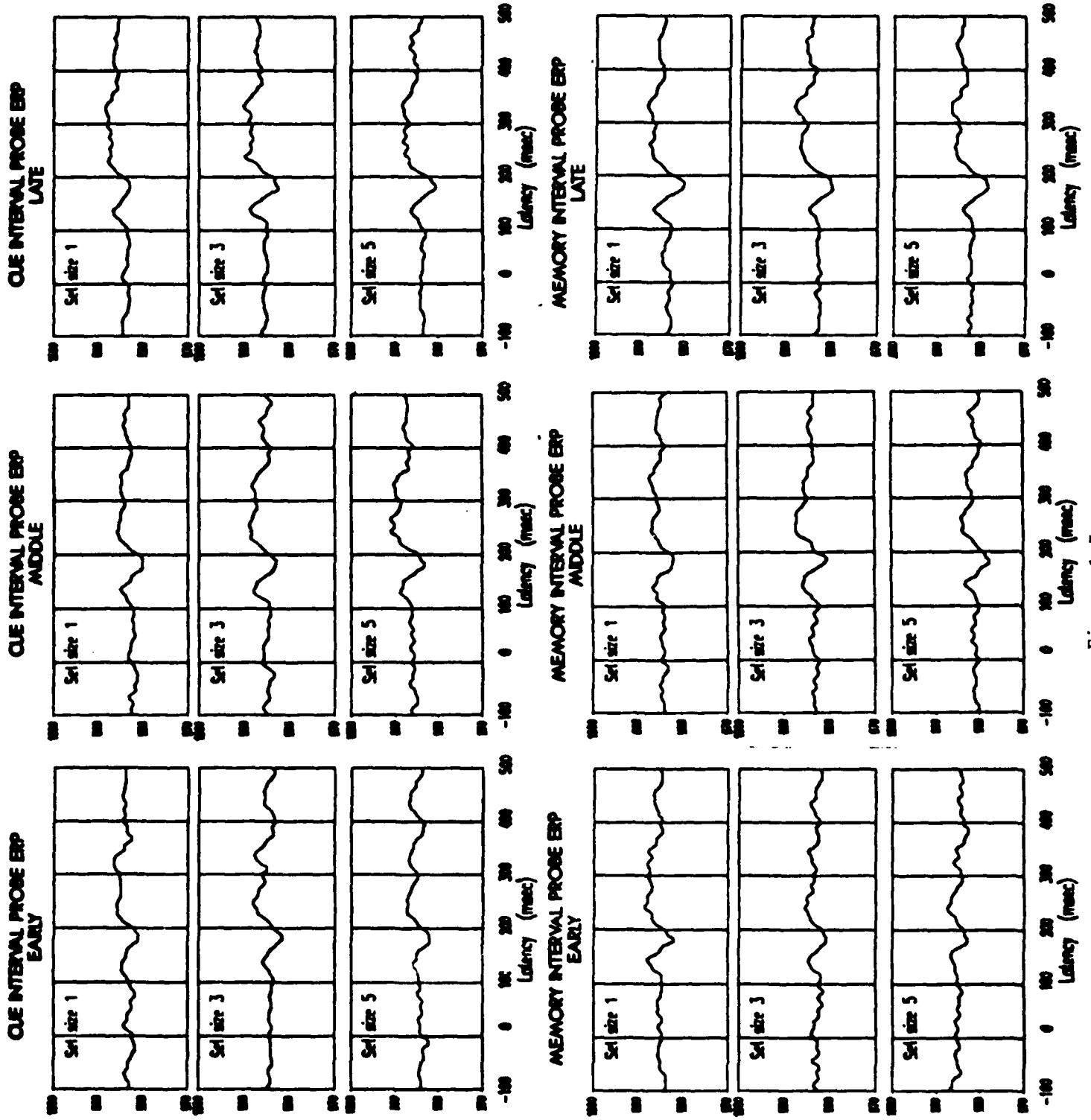
CUE INTERVAL PROBE ERP
EARLY
CUE INTERVAL PROBE ERP
MIDDLE
CUE INTERVAL PROBE ERP
LATE
MEMORY INTERVAL PROBE ERP
EARLY
MEMORY INTERVAL PROBE ERP
MIDDLE
MEMORY INTERVAL PROBE ERP
LATE
Set size 1
Set size 3
Set size 5
Latency (msec)

Figure 1.5

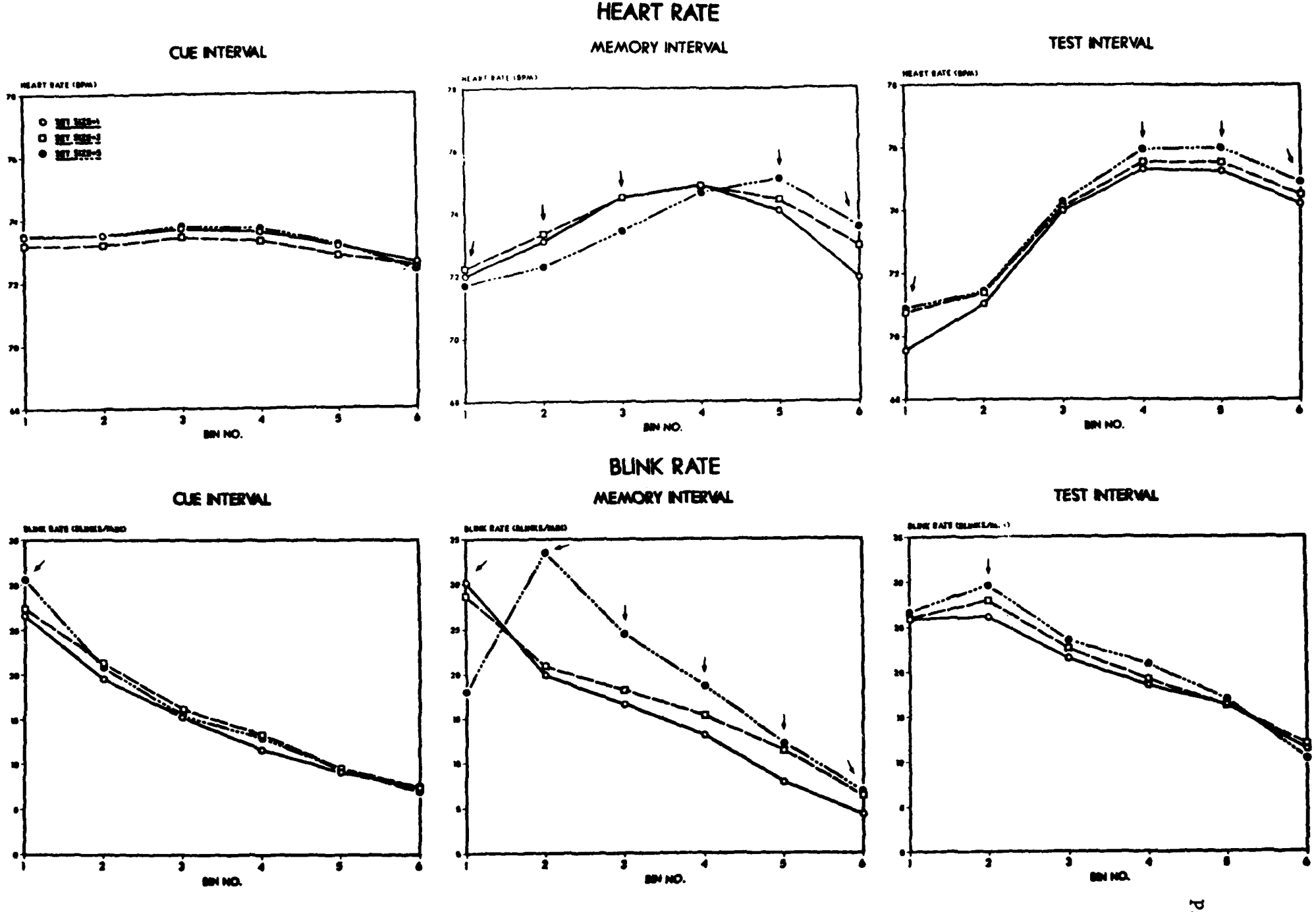
HEART RATE
CUE INTERVAL
MEMORY INTERVAL
TEST INTERVAL
BIN NO.
BLINK RATE
CUE INTERVAL
MEMORY INTERVAL
TEST INTERVAL
BIN NO.

Figure 1.6

BLINK LATENCY

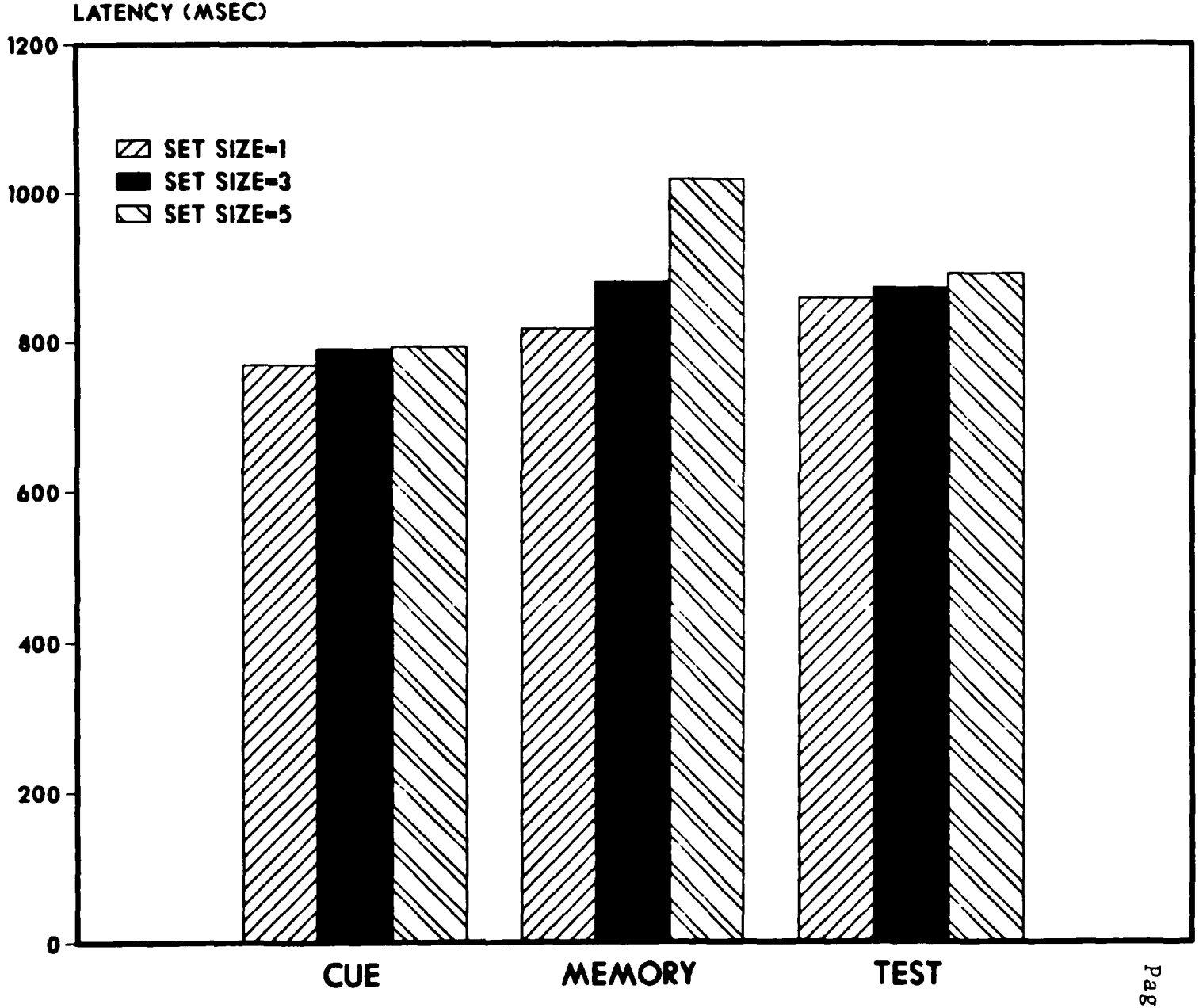

Figure 1.7

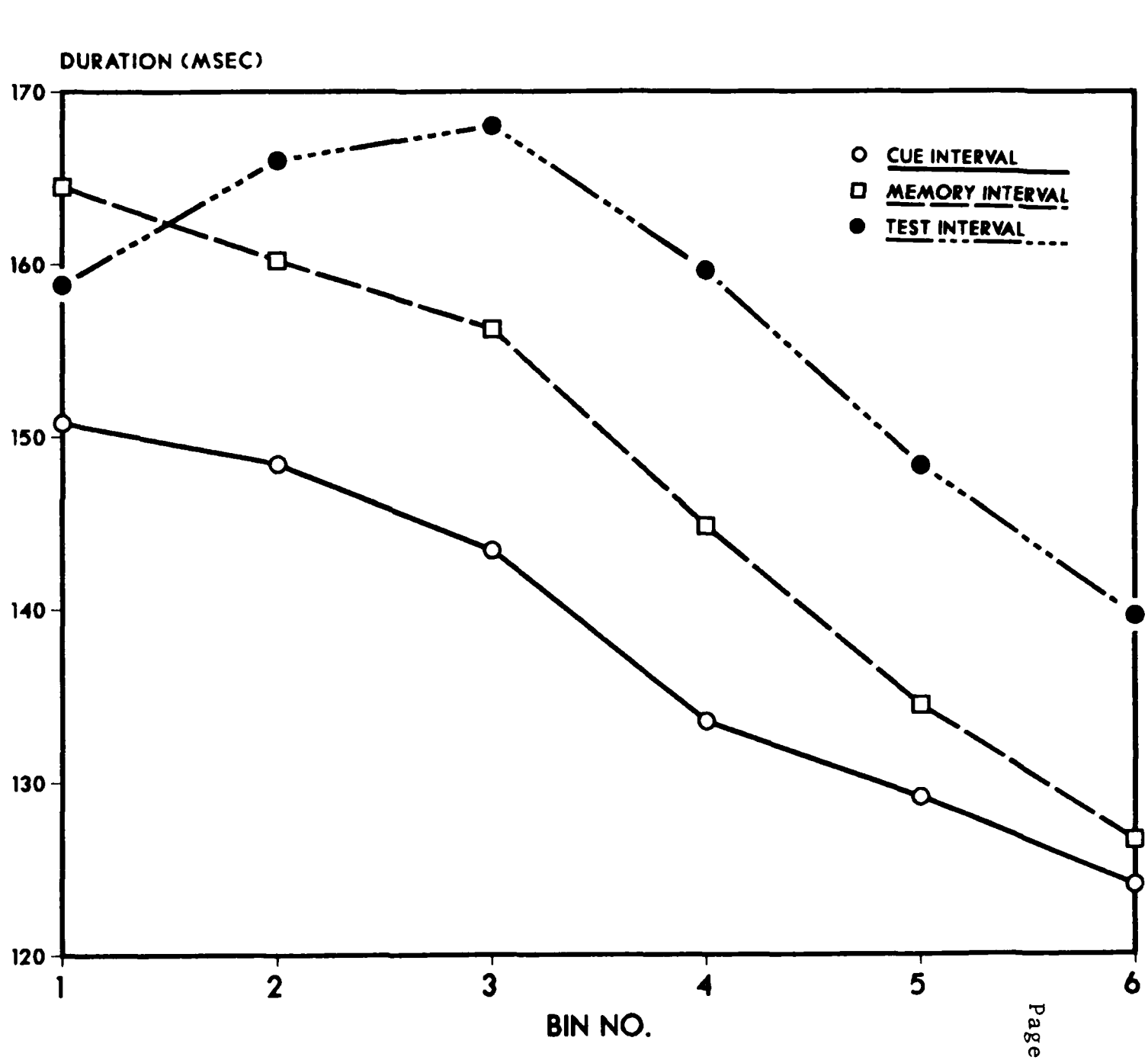
BLINK DURATION
DURATION (MSEC)
170
160
150
140
130
120
1
2
3
4
5
6
BIN NO.
CUE INTERVAL
MEMORY INTERVAL
TEST INTERVAL

Figure 1.8

REACTION TIME

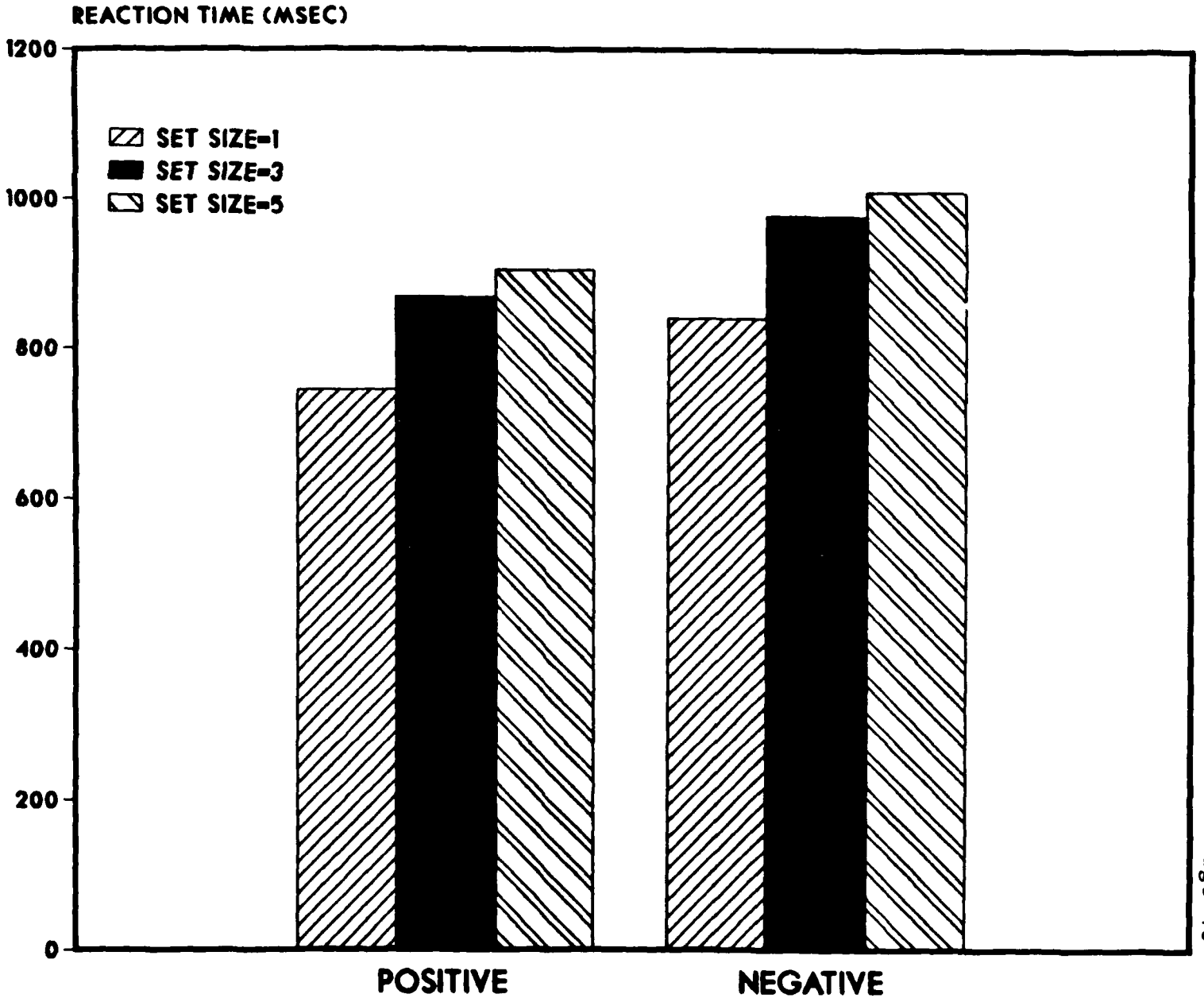

Figure 1.9

STUDY 2

EFFECT OF INFORMATION PROCESSING DEMANDS ON HEART RATE, BLINK PARAMETERS, AND EVENT-RELATED POTENTIALS TO TASK-RELEVANT AND IRRELEVANT STIMULI, AS A FUNCTION OF INTERSTIMULUS INTERVAL AND PROBE STIMULUS MODALITY.

INTRODUCTION

In the first study of this series (Bauer, Goldstein, & Stern, 1986), modulating effects of set size were observed in the EEG responses evoked by task-irrelevant probe stimuli. These effects were restricted to two temporal positions in the trial: late in the cue period and early in the memory period. The enhancement of P1-N1 magnitude late in the cue period was viewed as reflecting a graded priming of visual processes in direct proportion to the anticipated visual load. The absence of an analogous effect on heart rate and CNV argued against mediation of this effect by a topographically global, noncognitive process, e.g., a general activation. It was noted that the limited capacity model, which is the theoretical basis for the use of the probe technique, was contradicted by this amplification effect. The model would predict that an increase in task demands, or the anticipation of demands, by monopolizing processing capacity, would result in a reduced responsiveness to non-task stimuli, as was the case for the N1-P2 component during the retention of the memory set. But the validity of this argument does not preclude the

postulation of a generalization gradient along the dimensions of the stimulus parameters as well as of the processing demands evoked by the stimulus. This argument is no less persuasive with respect to the probe stimulus procedure than it is concerning the secondary task method of assessing reserve capacity (cf., Kramer, Wickens & Donchin, 1983, 1985). By using auditory probe stimuli in addition to visual probes, the present study is designed as a partial test of this hypothesis.

Another issue arising out of the previous study concerned the pattern of heart rate noted within the three task periods, and particularly within the memory period. Though heart rate did not reflect set size in the cue interval, it was sensitive to this variable in the memory period, exhibiting an initial relative slowing for the larger set size which reversed itself later in this interval. The possibility was mentioned that the relatively brief interstimulus interval could have distorted the full heart rate sequence (cf. Bohlin & Kjellberg, 1979). If so, increasing the interstimulus interval should be effective in revealing the full heart rate reflection of the underlying cognitive events, undistorted by anticipated events. This prediction was evaluated in the present experiment.

Finally, the blink rate data in the former study were particularly intriguing. This was especially true in the memory interval where blink rate showed an extraordinary sensitivity to underlying processes. The incidence of blinks for the largest set size was severely reduced at the outset of this interval. This early depression was followed immediately by a rebound of sufficient

magnitude to maintain the difference between set sizes for most of the memory period. Blink rate for the smaller set sizes exhibited a negatively accelerated descending trend over this period as was the case for all set sizes in the cue interval and, although to a lesser degree, in the test period. The interpretation offered, viz., that the increased time required for encoding of the memory set under high demand conditions produced the observed suppression of blink rate, was consistent with previous data (Goldstein, Walrath, Stern, & Strock, 1985) and was elaborated by the delayed blink latency for the large set size in the memory period. In spite of this consistency, however, the uniqueness of the effect suggests further documentation. The present study increased the maximum set size to six to put this hypothesis to the test.

METHOD

Subjects

Fourteen male Washington University students, aged 18-26, were paid for their participation in this experiment. All subjects were right-handed and had normal or corrected-to-normal vision.

Apparatus

The experimental room and the apparatus used for presentation of the task stimuli were as described in Study 1 of this report. The wattage of the probe light was reduced slightly from 7 to 6 producing a luminance change of from 15.05 to 14.36 cd/**m. In a preliminary matching procedure, it was roughly equated in brightness to the loudness of the auditory probe which was a 67 dB SPL tone (1000 Hz, 10 ms rise/fall) delivered through a speaker directly above

the subject's chair. To make the probes somewhat less intrusive, the duration of both the auditory and visual probe stimuli was reduced from 100 to 50 ms. In pilot work it was determined that the changed probes evoked reliable ERPs.

The same three measures of physiological activity were recorded as in the first study of this series. Scalp sites were Pz and Cz (International 10-20 System, Jasper, 1958). The Cz location was substituted for Fz to maximize the sensitivity to the auditory probes (Naatanen, 1982).

Procedure

A trial was defined by the sequential presentation of three "task" stimuli: a cue stimulus, a memory set, and a test stimulus, each 700 ms in duration. These appeared at regular intervals, i.e., either every 6 or every 10 sec, depending on the interstimulus interval. Six probe stimuli were interpolated among these task stimuli on every trial, two in each of the three interstimulus periods of the trial (hereafter referred to as the cue, memory, and test periods). Presentations of auditory and visual probe stimuli were randomly intermixed.

The six probe stimuli occurred at two temporal positions in each of the three interstimulus periods: "early" (1000, 1600, or 2200 ms following offset of the preceding task stimulus) and "late" (1000, 1600, or 2200 ms preceding onset of the subsequent task stimulus). This temporal relationship of the probe to the task stimuli was maintained irrespective of the duration of the interstimulus interval (ISI).

The experiment was administered in 4 blocks of 84 trials each

(divided over two days), in which each condition of the experiment (ISI duration, set size, membership (match/mismatch), probe stimulus modality) was represented equiprobably. Each block of 84 trials was further subdivided into 4 blocks of 21 trials, in which the duration of the interstimulus interval was fixed at either 5.3 (SOA=6 sec) or 9.3 (SOA=10 sec) sec. These ISIs were heralded, once at the beginning of each ISI trial block, by a message presented on a display next to the one used for presentation of the cue, memory, and test stimuli.

The instructions given to the subjects were similar to those used in Study 1. That is, subjects were instructed that the value of the cue stimulus (2 or 6) would indicate the number of letters that would appear in the following memory set after the designated time had elapsed. Subjects were instructed to commit the set to memory silently. Then, when the test stimulus appeared, again after the designated time had elapsed, they were to execute a discriminative reaction time response indicating whether or not the test stimulus was a member of the memory set. For one-half of the subjects, this meant that they were to move a joystick to the right for a "yes" and to the left for a "no". For the remaining subjects, this was reversed.

RESULTS

Event-Related Potentials

Results from the analysis of the Task ERPs and of the Probe ERPs, for each lead, will be presented separately. As in Study 1, the analytic procedure for both Task and Probe ERPs was a

multivariate ANOVA (MANOVA). Univariate analyses are reported only when the test for that variable was significant in the overall MANOVA. As further protection against false rejections of the null hypothesis, given the extraordinary number of tests performed, a more conservative 98% confidence level was adopted. Only those findings that met this criterion will be reported.

Task ERPs

Parietal Derivation. Group-averaged cue, memory set, and test ERPs, recorded at Pz, for each combination of the Interstimulus Interval (short/long), Period (cue/memory/test), Set size (small/large), and Membership (match/mismatch) factors are presented in Figure 2.1.

Insert Figure 2.1 about here

There are several interesting aspects of the waveforms. Note that, as in the previous study, there are identifiable positive-going waves in the vicinities of 100, 200, and 280 ms, and negative-going waves in the vicinities of 120 and 230 ms post-stimulus onset. The pattern of effects manifest in these waveforms was quite complex.

First, there were distinct differences among the cue, memory set, and test ERPs (Manova $F(12/42)=3.6$, $p<0.001$) in terms of both P2 ($F(1.5/19.6)=6.1$, $p<0.02$) and CNV ($F(1.6/21.5)=13.9$, $p<0.0005$) amplitude. The P2 component was, in general, more positive in the memory and test ERPs than in the cue ERP. The CNV was more negative preceding the test stimulus than it was preceding the cue and memory set stimuli. Second, the membership, or lack thereof, of the test

stimulus in the memory set differentially affected the amplitudes of the P1 and N1 components elicited by the cue, memory set, and test stimuli (Membership x Stimulus: Manova $F(12/42)=3.5$, $p<0.01$; P1: $F(1.9/24.1)=4.8$, $p<0.02$; N1: $F(1.8/23.1)=5.9$, $p<0.01$). Simple effects tests of the Membership effect at each level of the stimulus type variable indicated that matching test items evoked a larger N1 than mismatching ones. Tests of the "Membership" effect applied separately to the cue and memory ERP (where the "Membership" designation was only nominal) were not statistically significant. And finally, although it is not obvious from a visual inspection of the group-averaged waveforms, P1 amplitude varied in a complex manner as a function of Interstimulus Interval, Membership, and Set Size variables (Manova $F(6/8)=9.3$, $p<0.01$; Univariate $F(1/13)=14.1$, $p<0.01$). No combination of simple effects tests made this result interpretable.

Vertex Derivation. The results of the analysis of the vertex-derived task ERPs generally replicate the results just presented. In this analysis, P2 amplitude was again found to be larger in the memory set and test ERP than in the cue ERP (Manova $F(12,42)=4.2$, $p<0.001$; Univariate $F(1.5,19.6)=17.5$, $p<0.001$), and the CNV was found to be larger preceding the test stimulus than it was preceding the cue and memory set stimuli ($F(1.6,21.4)=5.2$, $p<0.02$). The Stimulus Type x Membership interaction (Manova $F(12,42)=3.2$, $p<0.01$) for P3 ($F(1.7,22.3)=14.9$, $p<0.001$) was significant though the univariate analysis for P3 was short (.046) of the more rigorous .02 alpha level in this study. The Interstimulus Interval x Membership x Set Size interaction, found in the analysis of the parietal data, was not

replicated in the vertex data.

Probe ERPs

The treatment of the probe ERP data is divided into two sections. The first examines the ERPs elicited by visual probes and the second section is concerned with the auditory probe ERPS.

Visual Probe ERPs

Parietal Derivation. (Figure 2.2). One main effect and one interaction attained significance in this analysis. The overall

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Insert Figure 2.2 about here

Probe Position effect was significant (Manova $F(5,9)=10.0$, $p<0.002$) and the Univariates were significant for P1-N1 ($F(1,13)=27.38$, $p<0.001$), N1-P2 ($F(1,13)=23.4$, $p<0.001$), and P2-N2 ($F(1,13)=16.3$, $p<0.01$). In addition, the overall Period x Position interaction was significant (Manova $F(10,44)=3.2$, $p<0.01$). Significant univariates were obtained for N1-P2 ($F(2,25.9)=6.1$, $p<0.01$) and P2-N2 ($F(2,24.5)=8.7$, $p<0.002$). With respect to the Position effect, the P1-N1, N1-P2, and P2-N2 amplitudes were greater at the early probe position than at the later one. The Period x Probe position interaction reflected the fact that the decline was evident in the cue and memory periods but not in the test periods.

Vertex Derivation. Analysis of visual probe ERPs recorded at Cz yielded two significant effects. The first was a Position main effect (Manova $F(5,9)=16.5$, $p<0.001$) which manifested itself in significant Univariates for P1-N1 ($F(1,13)=20.6$, $p<0.001$), N1-P2 ($F(1,13)=72.7$, $p<0.0001$), P2-N2 ($F(1,13)=41.7$, $p<0.001$), and N2-P3 ($F(1,13)=7.24$,

$p<0.02$). The second was a Probe Position x Period interaction (Manova $F(10,44)=2.9$, $p<0.01$) for CNV amplitude (Univariate $F(1.6,21.2)=7.3$, $p<0.01$). The Probe Position main effect was in the same direction as noted for the parietal lead. The Probe Position x Period interaction indicates that while the CNV, became less negative as the period progressed, this recovery occurred at a greater rate in the memory period than in either the cue or test periods.

Auditory Probe ERPs

Parietal Derivation. Analysis of auditory probe ERPs, recorded at Pz, yielded one significant effect, a Probe Position x Period interaction (Manova $F(10,44)=2.84$, $p<0.01$) for P2-N2 (Univariate $F(1.8,23.7)=8.2$, $p<0.01$). Simple effects tests attribute this effect to declines in P2-N2 amplitude over Probe Positions in the cue and memory periods coupled with an increase in this component in the test period. All three of these simple effects were insignificant ($p=0.08$, $p=0.10$, $p=0.08$, respectively).

Vertex Derivation. Analysis of auditory probe ERPs, recorded at Cz, also yielded one significant effect, an Interstimulus Interval main effect (Manova $F(5,9)=5.6$, $p<0.02$). Univariate tests attributed this to P1-N1 ($F(1,13)=10.2$, $p<0.01$) which was of greater magnitude on 10 sec ISI trials than on 6 sec ISI trials.

Heart Rate (HR)

As noted earlier, each of the three periods in a trial was divided into one second bins commencing with the onset of the task stimulus in that period. Absolute HR was calculated for each bin

(six, for the short ISI, and ten, for the long ISI). These data are displayed in Figure 2.3.

Insert Figure 2.3 about here

In order to analyze the interstimulus interval effect and its interactions properly, while retaining the essential information in these data, three points were abstracted from each period. These were: the minimum HR in the first two bins, the minimum HR in the last two bins (bins 5 and 6 for the short ISI and bins 9 and 10 for the long ISI), and the maximum HR in the intervening bins. Match

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Insert Figure 2.4 about here

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and mismatch trials were pooled for this analysis. The resulting data are plotted in Figure 2.4.

The Period effect was significant ($F(1.9, 25.0)=7.84$, $p=.0025$). Qualifying the Period effect was a significant Period X ISI interaction ($F(1.6, 21.3)=13.5$, $p=.0003$). Simple effects tests, following up this interaction, documented a significant ISI difference in the Memory interval ($F(1, 13)=9.9$, $p=.0078$) but not in either the Cue or Test intervals. Although Period interacted with Setsize ($F(1.91, 24.8)=5.87$, $p=.0088$), none of the individual Setsize comparisons for the three periods was significant (p values were .35, .08, and .28, respectively, for the cue, memory, and test periods). It would appear (cf., Figure 2.4) that the source of the interaction lay in the relative direction of the set size effect in the three

periods, viz., HR for the six letter set was greater than for the two letter set in the cue and test periods and less than for the two letter set in the memory period).

The main effect of Peak (differences among minima and maximum) was also significant ($F(1.4, 18.3)=73.0$, $p<.0001$). This was qualified by two-way interactions of Peak with each of two other variables: ISI, and Period. With respect to the interaction with ISI, clearly the peak differences were more extreme for the long than the short ISIs, accelerating to a higher level and decelerating to a lower level at the termination of each period. Concerning the interaction of Peak with Period, HR fluctuation in the memory interval appeared to be damped compared to the other periods.

A second analysis was performed to assess differences in the latency to the peak acceleration. The bin number (1 to 6) showing the maximum acceleration was used for this analysis. Despite the crudeness of this measure, two significant main effects emerged, as is suggested in Figure 2.3; namely, ISI ($F(1, 12)=47.0, p<.0001$) and Period ($F(2, 23.6)=7.27, p=.0036$). HR peaked later for the longer ISI; peak HR also was achieved earliest in the cue period, next in the memory period, and latest in the test period.

Blink Data

Blink Rate

Blink rate was also determined for each one second time bin across the trial and expressed in terms of blinks/minute (Figure 2.5). These data were subject to two main ANOVAs: the first dealt

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Insert Figure 2.5 about here

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only with the first six bins for both ISIs; the second concerned the remaining four bins (7-10) of the long ISI trials.

In the first analysis, two main effects were significant: Bin ($F(2.8, 37.0)=18.56$, $p<.0001$), and Period ($F(1.6, 21.5)=8.78$, $p=.003$). The source of the Bin effect is obvious; rate declines precipitously from a high (25.2/min) at the outset of the period to a low (15.3/min) in Bin 6. Equally clear is the fact that the rate change over bins depends jointly on the period and the set size (the Bin X Period X Setsize interaction was significant: $F(2.5, 32.6)=12.33$, $p=.0001$). Whereas rate declined monotonically in the cue and test periods for both set sizes and both ISIs, this was not the case in the memory period. There, for the large set size only, rate started from a low level in bin 1, increased to a high in bin 2, and thereafter declined as in the other periods. The effect was sufficiently robust to manifest itself in a significant Bin X Period ($F(3.[illegible], 51.2)=5.39$, $p=.001$) and Bin X Setsize interaction ($F(2.7, 34.9)=12.22$, $p<.0001$), which are uninformative by themselves. Finally, the Bin effect was qualified by an interaction with ISI ($F(2.4, 31.1)=7.83$, $p=.001$). Thus, for the longer ISI, blink rate did not decline over time as rapidly as for the short ISI (ISI differences were significant for the fifth bin in the Memory period and for the sixth bin in both Cue and Memory periods; all p-values $<.003$).

The results of the blink analysis for the final four bins of the long ISI were not unusual. The only significant effect was the main

effect for Bin ($F(2.2, 28.2)=10.12$, $p=.0004$); the rate decline initiated in the first six bins simply continued. Consistent with the ISI differences described above, an analysis of rate in the last bin only (Bin 6 for the short ISIs and Bin 10 for the long ISIs) yielded no significant main or interaction effects. Apparently, blink rate decreased to the same asymptotic level at the end of the period, regardless of ISI, but approached the asymptote at different rates.

Blink Latency

Latency of the first blink after each of the three task stimuli, plotted in Figure 2.5 (bottom panel), was subject to a 2X2X2X3 ANOVA, with ISI, Match/Mismatch, Setsize, and Task stimulus as the variables. Two of the main effects were significant: Setsize ($F(1, 13)=7.29$, $p=.0182$), and Task Stimulus ($F(2.0, 25.5)=6.52$, $p=.0054$). Although the setsize effect appears to be restricted to the memory stimulus, the interaction of Task Stimulus X Setsize did not achieve significance by the criterion adopted here.

Blink Duration

Bin by bin blink duration data are displayed in Figure 2.6. The data were analyzed in a similar manner to blink rate, viz., two

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Insert Figure 2.6 about here

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separate ANOVAs: the first on bins 1-6 under both ISI conditions, and the second on the remaining bins (7-10) of the long ISI condition.

Significant main effects in the first (1-6) ANOVA were: ISI ($F(1, 12)=26.69$, $p=.0002$), Bin ($F(1.6, 19.2)=13.0$, $p=.0005$), and Period ($F(1.9, 23.0)=19.51$, $p<.0001$). The ISI effect indicated that the

duration of blinks was shorter when ISI was 6 sec than when it was 10 sec. The significant Bin effect supports the observation that blink duration declines within periods. With respect to the Period effect, blink duration apparently increases across periods within a trial. Although there was a significant Match/Mismatch X Period interaction, the difference between match and mismatch conditions was greatest for the Cue period, where the "Match/Mismatch" designation was only nominal, but practically identical for the other periods, an anomalous finding.

In the second ANOVA, the Period effect of the first ANOVA was sustained ($F(1.5, 18.4)=8.56$, $p=.0041$). The Setsize X Period interaction was also significant ($F(2.0, 24.0)=4.79$, $p=.0179$). Though the source of this interaction appears to lie in the difference between set sizes in the memory period (duration for the 6-letter set was longer than for the 2-letter set) as compared to the differences in the Cue and Test periods, none of the individual comparisons of Setsize for the three periods was significant.

Finally, as was the case for blink rate, blink duration in the final bin of each ISI did not differ (mean for the short ISI = 138 msec and for the long ISI = 139 msec).

Performance

Reaction Time

A median RT was obtained for each subject in each experimental condition. Trials on which an incorrect decision was made were excluded from the RT analysis; error rates are reported below.

A 2 (interstimulus interval) x 2 (set size) x 2 (membership)

repeated measures ANOVA was performed on the median correct RTs (Figure 2.7, left panel), which demonstrated that (for both positive

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Insert Figure 2.7 about here

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and negative judgments) there was a nonsignificant ($F(1,13)=4.51$, $p=0.053$) increase (111 ms) in RT as a function of set size. Processing time per item was 29 ms for match and 26 ms for mismatch trials. The ANOVA also demonstrated that the membership factor (match/mismatch) was significant ($F(1,13)=29.6$, $p<0.001$). Reaction times were found to be 202 ms longer, on the average, for correct negative judgments than for correct positive judgments.

Response Accuracy

The effects of Interstimulus Interval, Setsize, and Membership on arcsine-transformed error rate were examined in a three way analysis of variance. The data are plotted in the right panel of Figure 2.7. There was a markedly higher error rate found for the large, than for the small, set size ($F(1,13)=15.7$, $p<0.01$). Error rates for positive and negative judgments did not differ significantly.

DISCUSSION

In this study, several alterations were made to the procedure of study 1 in order to ascertain the undistorted cardiac response to task events and to explore the relationship between the probe and

task modalities in the probe ERP effect. For these purposes, two additional variables were introduced: a ten second SOA condition was added to the 6 sec SOA, and second, probe stimuli were divided between auditory and visual modality. Further, to reduce the salience of the probe stimuli, the intensity of the visual stimulus was reduced somewhat and its duration was halved. In addition, the striking effect of processing load on blink parameters, especially rate, noted in the first study, was singled out for special attention.

With respect to the effects of these procedural changes on probe ERPs, the results were disappointing. In study 1, P1-N1 and N1-P2 were enhanced as task stimuli became imminent, an effect that was interpreted in terms of a growth in the mobilization of a selective attentional process, a specific priming effect (cf., Bauer, 1982). It was noted then, that this did not accord with a limited capacity model (Navon & Gopher, 1979; Papanicoulaou & Johnstone, 1979), and, in fact, contradicted it. The present visual ERP data robustly reversed the prior observation, yielding, instead, an <u>increase</u> in amplitude within periods, and extended it to later ERP components (a point that will be discussed below). It should be noted that a reanalysis of the present data restricted to the short SOA, to make it analogous to the first study, did nothing to change this effect, which was observed at both Cz and Pz. Thus, the present results are in agreement with a limited capacity model, but only in a limited way.

That the position effect was present only in the cue and memory periods and not in the test period, may be seen as supporting this

view. It is consistent with the intuitively acceptable assumption that the events terminating the cue and memory periods (viz., the memory set and the test stimulus, respectively) were of greater significance to the subjects than the cue stimulus, which followed the test interval. Thus, as mechanisms were being brought to bear to process upcoming stimuli, less neural circuitry was available to handle the probes. The absence of these effects in response to auditory probes is also compatible with this interpretation.

Serious inconsistencies with this interpretation can not be overlooked. First is the absence of a set size effect or any interaction with set size. This implies that while preparation for cognitive events is associated with a reduction in responses to probe stimuli in a global way, the magnitude of the anticipated load, at least represented by the range of loads sampled here, is not mirrored in the magnitude of the reduction. Ignoring, for the moment, the difference in the direction of the effect in the two studies, explanation of the absence of set size effects here might proceed as follows: the set size differences observed in study 1 were between a set size of one and set sizes of three and five; the latter two did not differ from one another. Here, the pattern resembled the that produced by the larger two set sizes. The relatively high error rate for the large set size here, discussed below, suggest a partial answer; it will be argued that somewhat less than the full six letters were apprehended, on the average. This would functionally reduce the difference between the sizes of the sets and make it less likely to demonstrate a set size effect, especially with the omission of the one-item set which produced the largest contrast in study 1

and other work (Gomer, Spicuzza, & O'Donnell, 1976). These speculations could be validated if the exposure time of the memory set were increased to insure the apprehension of the full set.

The second issue concerns the predicted direction of the position effect in the cue and memory intervals. Though prediction of a decline in amplitude in the cue period and its absence in the test period can be accepted, the relative significance of cognitive events at the two probe positions in the memory interval is less evident. At the early probe position, the subject is processing the memory set; at the end of the memory period, he is preparing to acquire the test stimulus, compare it with the memory set, and respond. Although one may have a bias as to which of these functions is more significant for the subject, and thus to predict the direction of the effect, the present data provide no way of validating this bias.

What the critical difference is between the two studies is not clear. Reduction in the intensity and duration of the visual probe may be relevant. Preliminary work suggested that the altered probe stimuli would still evoke identifiable ERPs (and this is also true with regard to the auditory probe). Reducing probe salience, it was felt, would maximize the possibility of producing results compatible with a limited capacity model. But this, as was seen, was not unambiguously supported.

The possibility that the mix of visual and auditory probe stimuli in the same context may underlie the probe results, similarly does not appear to be a useful explanation. Making the probe stimuli more unpredictable in content in this way does not appear to put a bias on the ERP amplitudes of either the early or the late probe.

Another aspect of the probe data, alluded to earlier, suggest caution in interpreting the probe data. Not only were there the above discrepancies with study 1, but the fact that all measured components showed the effect, not only the early ones, as in study 1, presents a problem. The probe stimuli are selected so as to demand as little higher order processing as possible.

The Task ERP data were also only marginally similar to those found in Study 1. The existing discrepancies are probably related to subtle differences in the details of the paradigms, such as the set sizes used. It will be recalled that, in Study 1, set size significantly affected the amplitudes of Memory and Test ERP components, whereas in the present study, set size had no effect on these ERP amplitudes. The explanation offered above for the absence of a set size effect with the probe stimuli is equally relevant here. Thus, Study 1 yielded a set size effect because the set sizes used (1, 3, and 5 items) included the major accelerating portion of the set size/probe amplitude function, whereas Study 2 failed to yield a set size effect because this portion of the function was not sampled.

How can the statistically significant results be interpreted in terms of what is known about information processing and event related potentials? First, the enhancement of Memory and Test ERP P2 amplitude, relative to Cue ERP P2 amplitude, at both Pz and Cz, must be reflecting the added demands placed on the encoding process by the Memory and Test stimuli. In other experiments (e.g., Chapman, McCrary, and Chapman, 1981), a cue stimulus which must be encoded and on which some cognitive work must be performed has been shown to elicit a larger P2 component than a cue stimulus which serves mainly

as a warning signal. Perhaps the relatively smaller P2 evoked by the cue in the present context, and the absence of a set size effect on probe ERPs elicited subsequent to it, indicates that subjects were using the cue merely as a warning signal and were not abstracting the useful information contained therein.

A second finding, that CNV amplitude was larger preceding the Test stimulus than it was preceding the Cue and Memory stimuli, can be explained on the basis of response preparation. According to this view, the relatively larger CNV preceding the test stimulus may be taken as a sign of cortical priming, which accelerates the motor response emitted to the Test stimulus. This is supported by reports that CNVs of the highest amplitude precede responses with the shortest reaction times (for a review, see Rockstroh, Elbert, Birbaumer, and Lutzenberger, 1982).

A third and perhaps most interesting finding was the change noted in Test stimulus ERP P3 amplitude as a function of stimulus classification. A few theorists (Ratcliff, 1985) have suggested that subjects respond differentially to matching and mismatching test items because they are less certain of a mismatch judgment than they are of a match judgment. Since P3 amplitude appears to be inversely related to subjective ratings of certainty (Squires, Hillyard, and Lindsay, 1973), it follows that P3 amplitude would be smaller on mismatch trials than it was on match trials.

The cardiac and blink data provide a solid anchor against which to evaluate the ERP data. They document clearly the reliability in the processes predicted on the basis of the first study. As predicted by Bohlin & Kjellberg (1979) and us, the effect of the longer ISI was

a fuller cardiac sequence following each task stimulus. Specifically, HR for the longer ISI achieved its peak later, the peak was higher, and the subsequent deceleration was greater. A comparison of HR in the first and second studies (cf., Figures 1.6 and 2.3) reveals that the acceleration in the cue period of study 1, which was very slight and which is replicated in the small set size of this study, is converted into a substantial acceleration when a longer period permits.

The HR sequence within periods in this study confirms empirically the idealized HR topography described in the literature (Bohlin & Kjellberg, 1979; Lang, Ohman & Simons, 1978). The initial minor deceleration they show, and which these authors interpret as an orienting response, can be seen by comparing the HR in the final bin of each period with that in the first bin of the ensuing period. Neither this nor the following acceleration in the cue period are dependent on set size, indicating that the attention produced by the stimulus is generic; it reflects not the importance of the message conveyed by the cue, but only that there has been a message. This does not accord with the conclusion of Lang et al., that the acceleration is anticipatory in nature, and will reflect the interest value of subsequent events when the subject has to do something to insure the anticipated perception. Sensory orientation, which certainly characterizes the preparatory activity in the cue interval, is specifically mentioned by Lang as meeting this criterion.

The blink data are consistent with this interpretation. There, too, set size did not discriminate the response to the cue. The high initial level in this period and in the test interval should best be

viewed as a response that follows the reading in of a significant stimulus. The fact that the rate is high indicates that these encoding functions, which tend to supress blinks, are consuming only minimal time. This is true also of the small set size in the memory period but not of the large set size in this period, as will be discussed below.

The HR deceleration at the end of each period also reflected the additional time permitted in the longer ISI; not only did the additional time produce a fuller acceleration, but following this, the final decelerative component was also extended. One conclusion that may be drawn from this is that the degree of acceleration following a signal can not be taken, by itself, as definitive evidence of a specific cognitive state. This is not implying, of course, that the differential acceleration, as a function of ISI, is to be thought of as an "artifact", a phenomenon unrelated to the underlying state. Five seconds following the task stimulus, for example, the subject is not in the same state in both ISIs. On short ISI trials, the decelerative HR trend may indeed indicate that he is preparing for reception of the next task stimulus whereas in long trials, continued high rates suggest that he may still be reacting to the previous stimulus. We would predict that this inferred shift in the subject's attention should be apparent in probe ERPs, assuming the inconsistencies described above can be worked out. In such an attempt, it would be necessary to increase the number of probe positions in the period in order to monitor the transition from one state to another.

As was the case in study 1, set size was unrelated to the

magnitude of the HR deceleration, whether or not the subject was permitted more time (longer ISIs) to prepare for the next stimulus. Once again we are forced to the somewhat paradoxical conclusion that while attention to an imminent stimulus provokes a sizable deceleration, degrees of significance of that stimulus are not graded in heart rate. The picture changes considerably when the memory period is entered. As is suggested in Figure 2.3, the size of the set is reflected in heart rate. This observation is not without its ambiguities. Though the Period x Setsize interaction was significant, it will be recalled that none of the individual set size effects for the three periods was significant; the only one that approached significance ($p=0.08$) was the memory interval. Since a false null with respect to the overall interaction is logically incompatible with the absence of a false null in any of the simple effects, we prefer to interpret the latter as a Type II error, and conclude that the set size difference, evident in the early part of the memory period, is a true effect. This is in agreement with study 1 although the reversal at the end of the memory interval was absent here. It also appears that this set size effect is absent as the subject mobilizes attention for the next task stimulus.

The blink data again offer convincing evidence of the effect of set size in the memory interval and are reminiscent of the same pattern observed in study 1. Here too, presentation of the larger set was accompanied by a strong inhibition in blinking (Figure 2.5), reinforcing the contention, expressed then, that this reflects a significant challenge to the subject's capacity to acquire the long memory set. And in further agreement with study 1, blink rate

increased, presumably after the large set was read in, indicating a transition from the encoding process into what was interpreted as the rehearsal function in study 1. The effect in the present study was even more accentuated. This adds strength to the argument that the HR deceleration for the large set in this period, is a concomitant of rehearsal, a point that was made in study 1.

Consistent with the heart rate data, blink rate also converged for the two set sizes within each ISI, as the test stimulus approached. It appears, once again, that the attention mobilized as a preparatory set for stimulus intake, is not sensitive to anticipated differences in cognitive work.

In both studies 1 and 2, the highest heart rates were seen in the test period. This was especially so for the long ISI in study 2 and is more marked if we consider the low initial HR for this condition in this period. This strengthens the contention that the acceleration is due to previous events rather than anticipatory of future events. The search is completed, the response has been executed, and the next stimulus, the cue, is of relatively little import. It is clear that response processes can produce marked accelerations (Bernstein, Taylor, Weinstein & Reidel, 1985) but what part of the present acceleration is due to that and what part to the search and comparison functions is undeterminable at this time.

Blink rate in the test interval exhibits a somewhat less precipitous decline than in the cue and memory periods. This seemed to be coupled with a higher final blink rate than in the cue and memory periods. This, too, replicates the pattern in study 1. It is tempting to conclude that the attentional requirements of the

upcoming cue stimulus are relatively minimal and therefore do not produce the same degree of inhibition. The absence of a preparatory set size effect at the end of the cue period in the present study suggests caution in this interpretation although it will be recalled from study 1 that a set size effect was demonstrated in this same context.

The pattern of blink latency observed in study 1 (Figure 1.7) was repeated in this study. The more conservative significance level chosen for this study, however, rendered the set size effect in the memory period insignificant (for both the Setsize x Period and the Setsize within Memory Period, the p-values was between .02 and .05). Empirically, set size seemed to affect blink latency only in the memory period (cf., Figure 2.5, bottom panel). It was at this point (Figure 2.5, center panel above), that a severe depression in blink rate was observed for the larger set size. These, then, are two sides of the same phenomenon; blinks are deferred at this point, presumably as the larger set is read in, which results in a lower blink rate in this bin. An interesting addendum to the blink latency data is the absence, in both studies, of any sign of a set size effect in response to the test stimulus. This contrasts sharply with the inhibition noted at the beginning of the memory period. Thus, while the encoding of information causes a temporary cessation of blinking, the comparison process, which involves retrieval and manipulation of stored information has no effect.

The relative reductin in blink duration in anticipation of the memory and test stimuli appears also to support the conclusion that these stimuli require a higher degree of attention than the cue

stimulus. All measures appear to concur in this conclusion: heart rate, blink rate, blink duration, and, with the expressed reservations, probe ERPs. With regard to the reduction in blink rate for the large set size at the outset of the memory period, those blinks that occurred were longer in duration than subsequent ones. Thus, blink duration does not carry information redundant with rate. Duration, unlike rate, is unaffected by the encoding of stimuli.

Mention should be made of the apparent anomaly in the performance measures. Unlike in study 1, RT was undifferentiated by the size of the set. This was accompanied by a set size difference in error rate which suggests a speed/accuracy tradeoff. Another explanation can be offered, already alluded to in the probe ERP discussion. That is, some of items in the six letter set may not have been perceived on all trials; if this were the case, then there would be fewer items in memory to scan; the search would still be at the same speed and still be exhaustive. The difference in RT for the two and six item sets indicates a scan rate of about 27.5 ms/item, considerably slower than the 41 ms rate in study 1, and that reported in the literature (Sternberg, 1966, 1975). If we accept 41 ms/item as a working value, the implication of the argument presented above, as applied to the present 111 ms difference between set sizes, is that the subjects acquired about 4.7 items on the average 6-item trial. This would be relevant not only to the set size effect in reaction time, but other variables as well.

In summary, the ERP data raised more questions than they settled. The changes in the procedure and the problem of complete acquisition of the larger set size may account for the discrepancy in

the ERP and RT results of the first and second studies. But if not, it dictates a reevaluation of the dimensions along which such marked variability takes place. The heart rate and blink data, in contrast, provide stable and sensitive indicators of underlying processes and, in fact, are of great help in providing a framework for hypothesing the source of the ERP problems.

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FIGURE CAPTIONS

Figure 2.1 Representative examples of group-averaged cue, memory set, and test ERPs, recorded at Pz, as a function of set size and membership.

Figure 2.2 Representative examples of group-averaged visual probe ERPs, recorded at Pz, as a function of set size, probe position, and period.

Figure 2.3 Absolute heart rate as a function of period, set size, interstimulus interval, and bin.

Figure 2.4 Heart rate as a function of period, set size, interstimulus interval, and peak.

Figure 2.5 (A) Blink rate as a function of period, set size, interstimulus interval, and bin.

(B) Blink latency as a function of period and set size.

Figure 2.6 Blink duration as a function of period, set size, interstimulus interval, and bin.

Figure 2.7 Reaction time as a function of membership and set size.

Figure 2.8 Error rate as a function of interstimulus interval and set size.

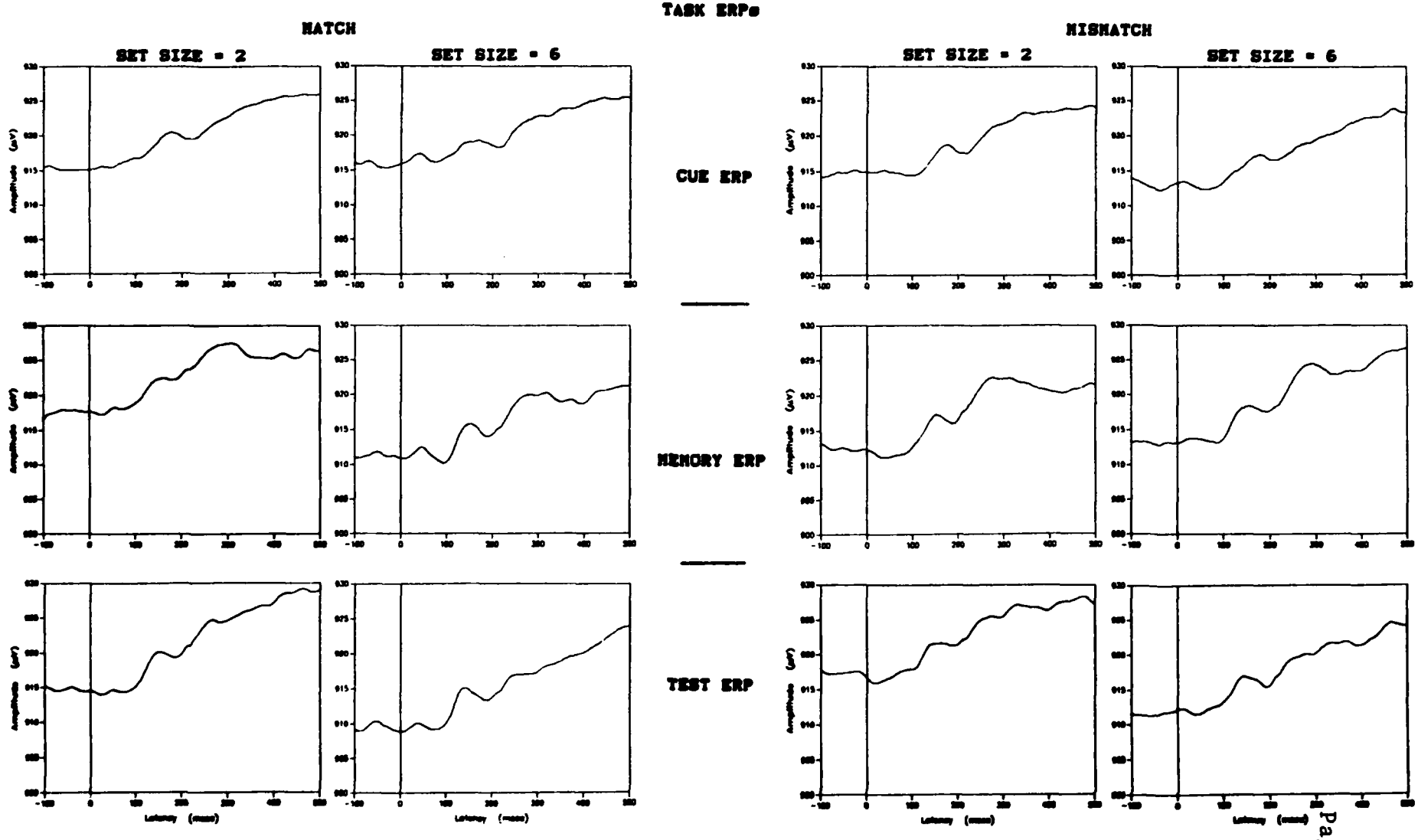

TASK ERPs
MATCH
MISMATCH
SET SIZE = 2
SET SIZE = 6
SET SIZE = 2
SET SIZE = 6
CUE ERP
MEMORY ERP
TEST ERP

Figure 2.1

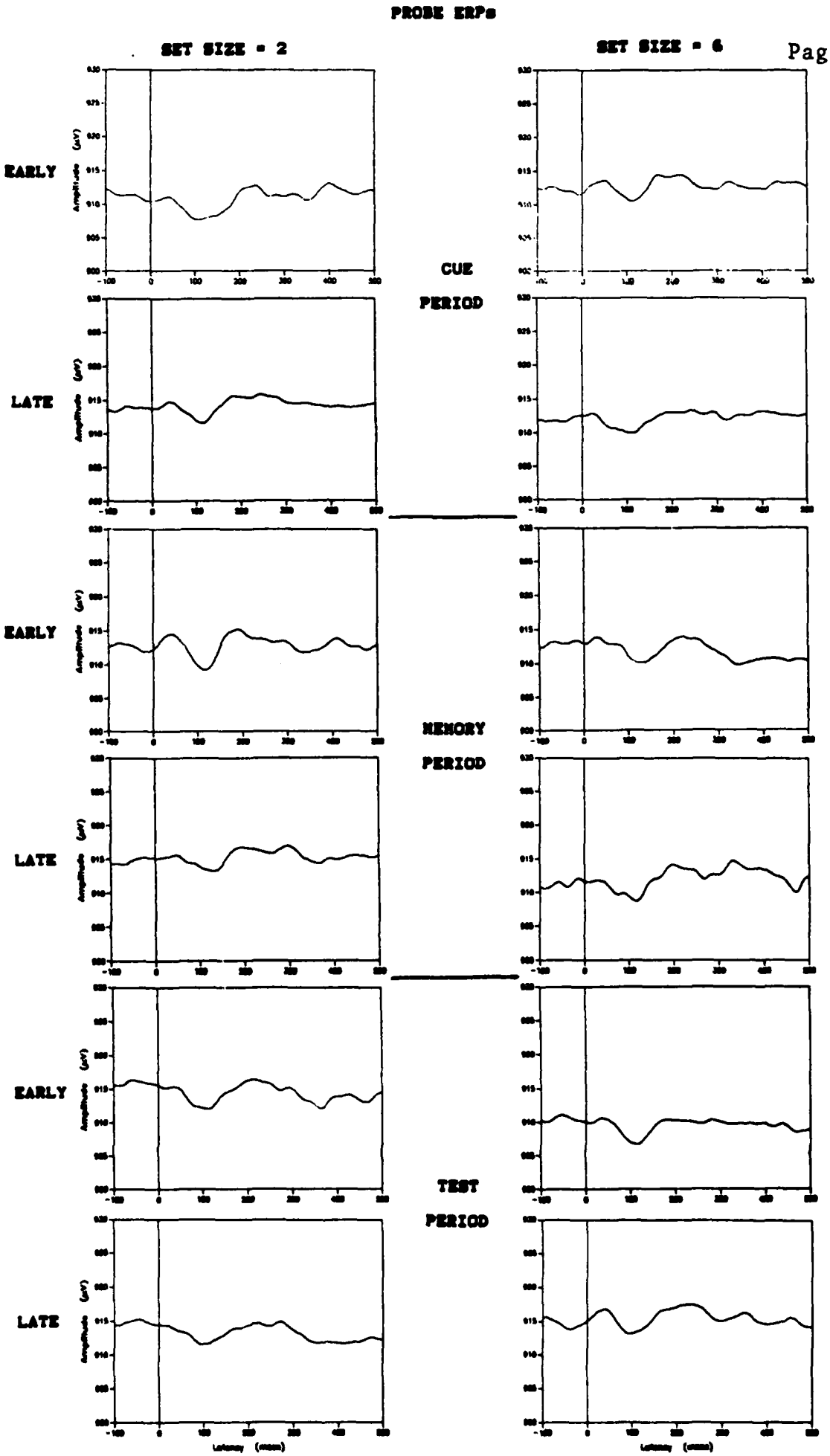

PROBE ERPs
SET SIZE = 2
SET SIZE = 6
EARLY
LATE
CUE
PERIOD
EARLY
LATE
MEMORY
PERIOD
EARLY
LATE
TEST
PERIOD
Amplitude (μV)
Latency (msec)

Figure 2.2

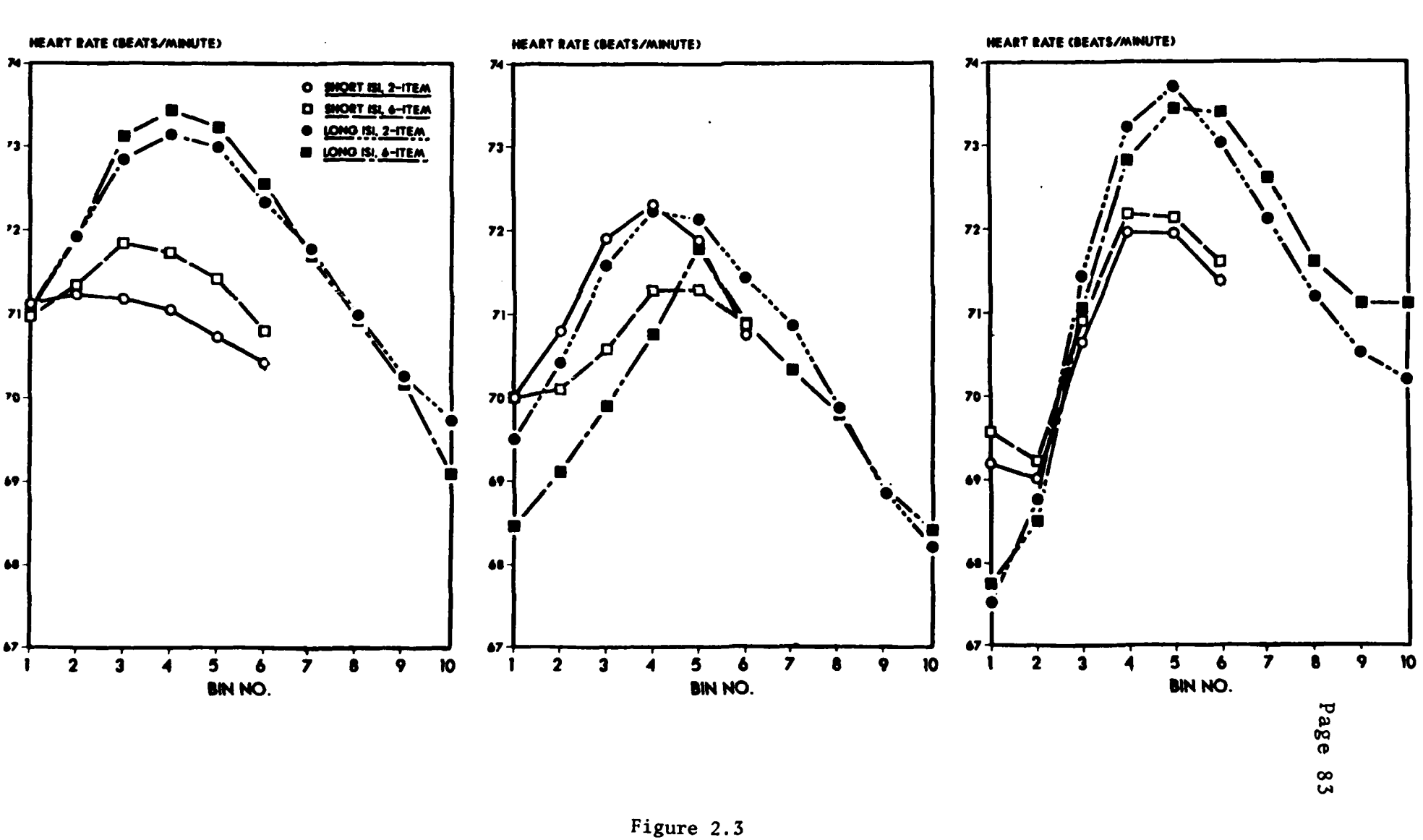

CUE PERIOD
MEMORY PERIOD
TEST PERIOD
HEART RATE (BEATS/MINUTE)
SHORT ISI, 2-ITEM
SHORT ISI, 6-ITEM
LONG ISI, 2-ITEM
LONG ISI, 6-ITEM
74
73
72
71
70
69
68
67
1 2 3 4 5 6 7 8 9 10
BIN NO.

Figure 2.3

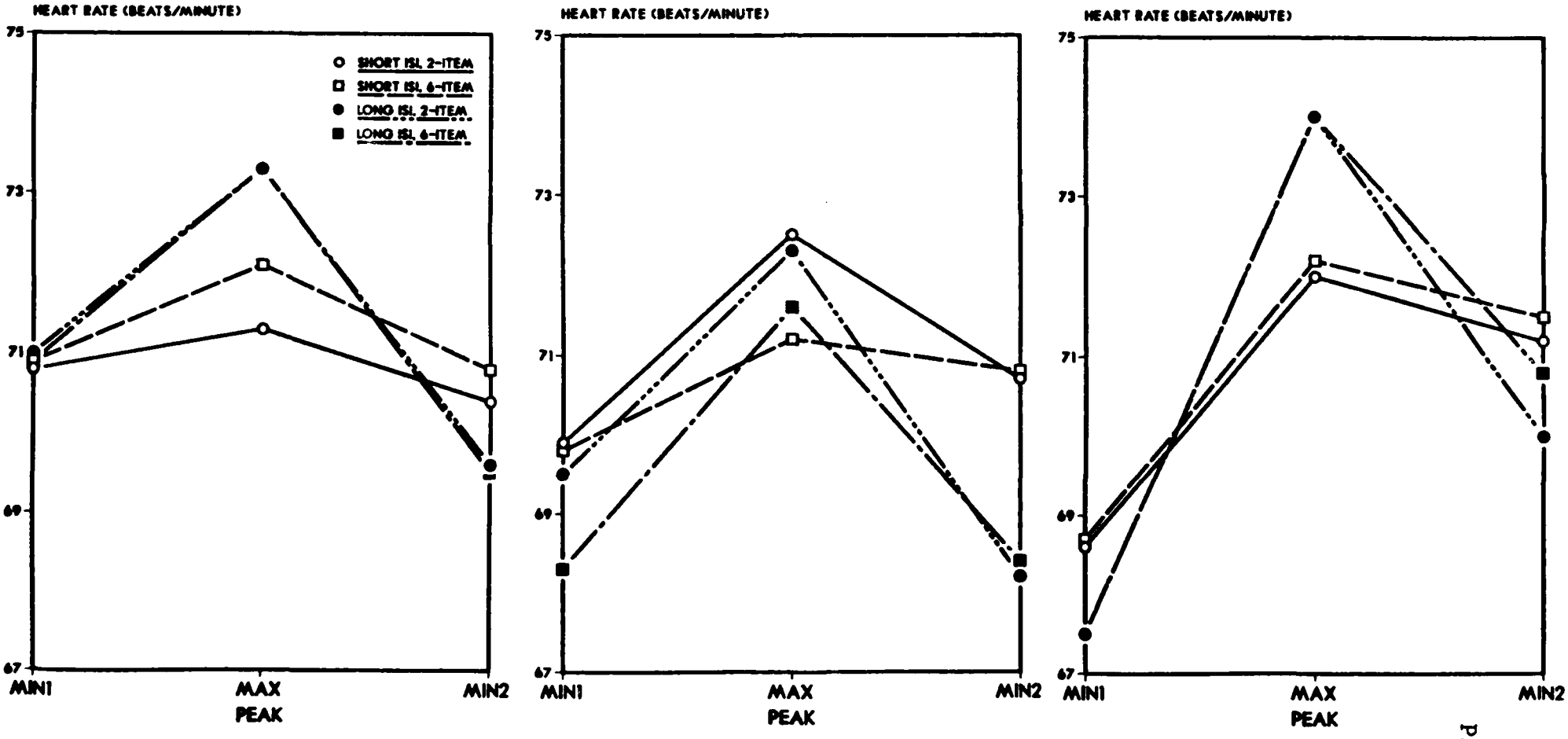
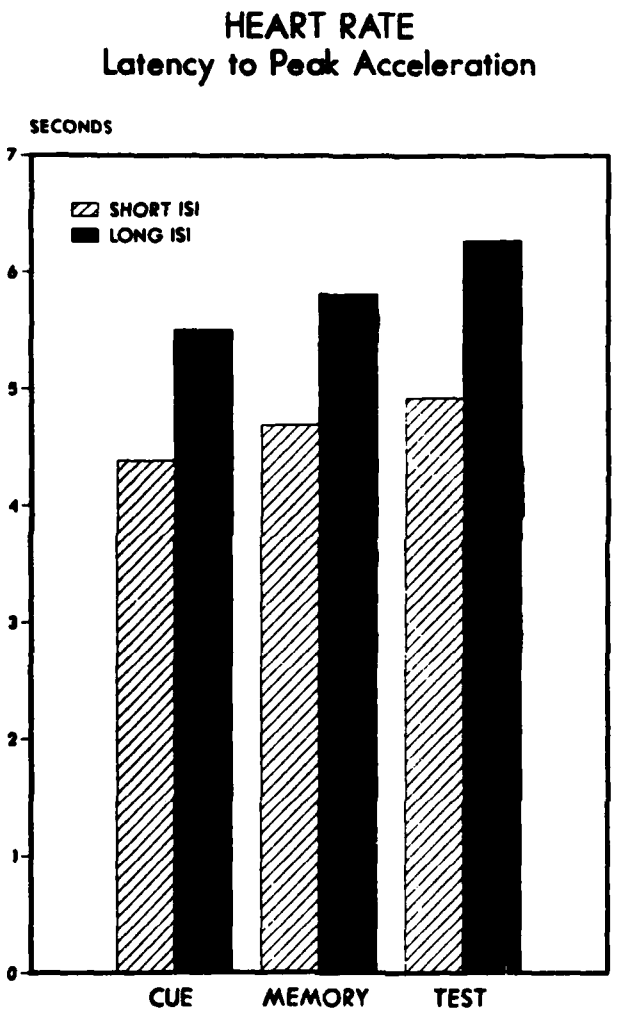

CUE PERIOD
MEMORY PERIOD
TEST PERIOD
HEART RATE (BEATS/MINUTE)
75
73
71
69
67
SHORT ISI, 2-ITEM
SHORT ISI, 6-ITEM
LONG ISI, 2-ITEM
LONG ISI, 6-ITEM
MIN1
MAX
PEAK
MIN2

Figure 2.4

Figure 2.5


HEART RATE
Latency to Peak Acceleration
SECONDS
7
6
5
4
3
2
1
0
SHORT ISI
LONG ISI
CUE
MEMORY
TEST

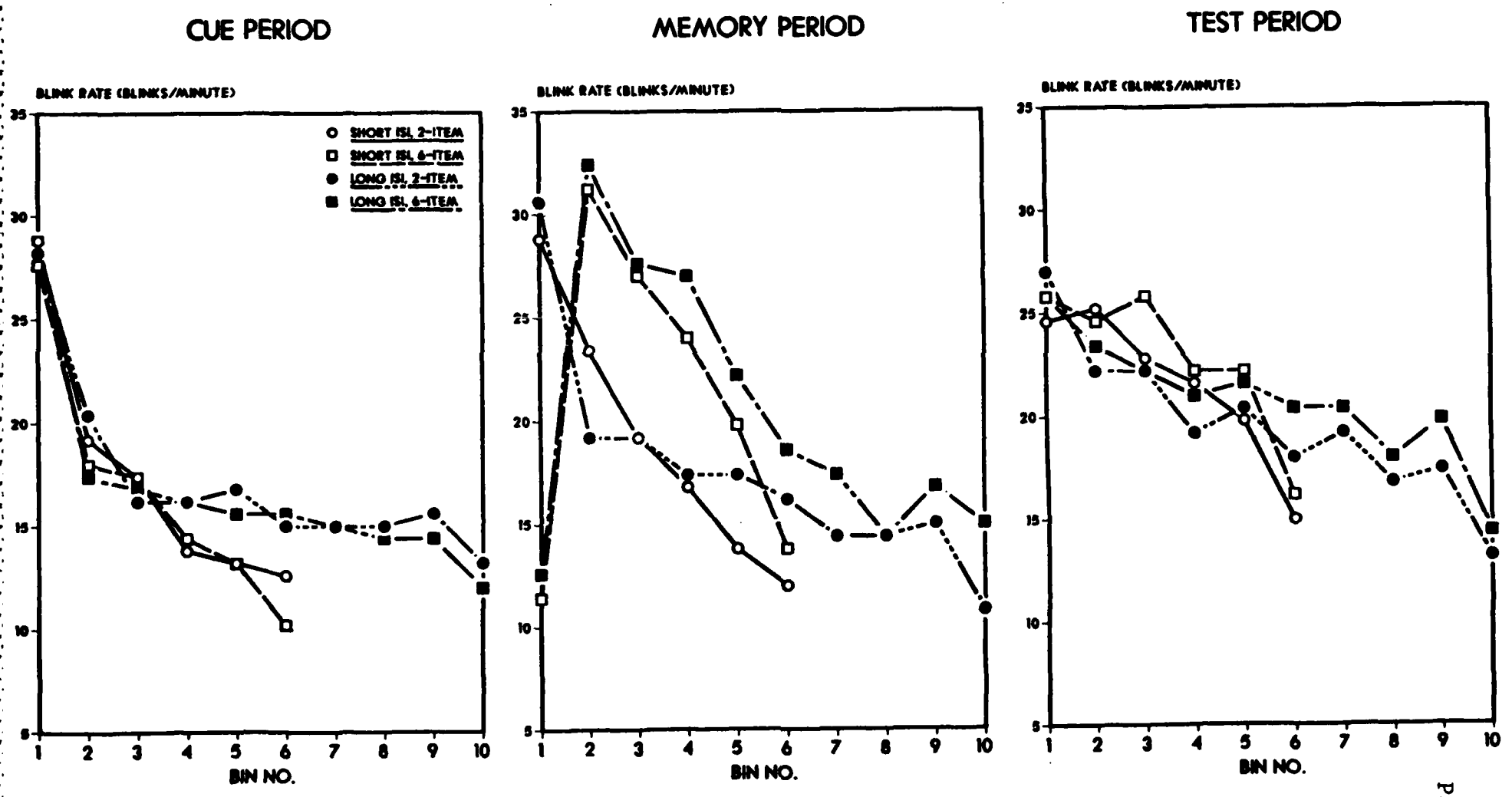
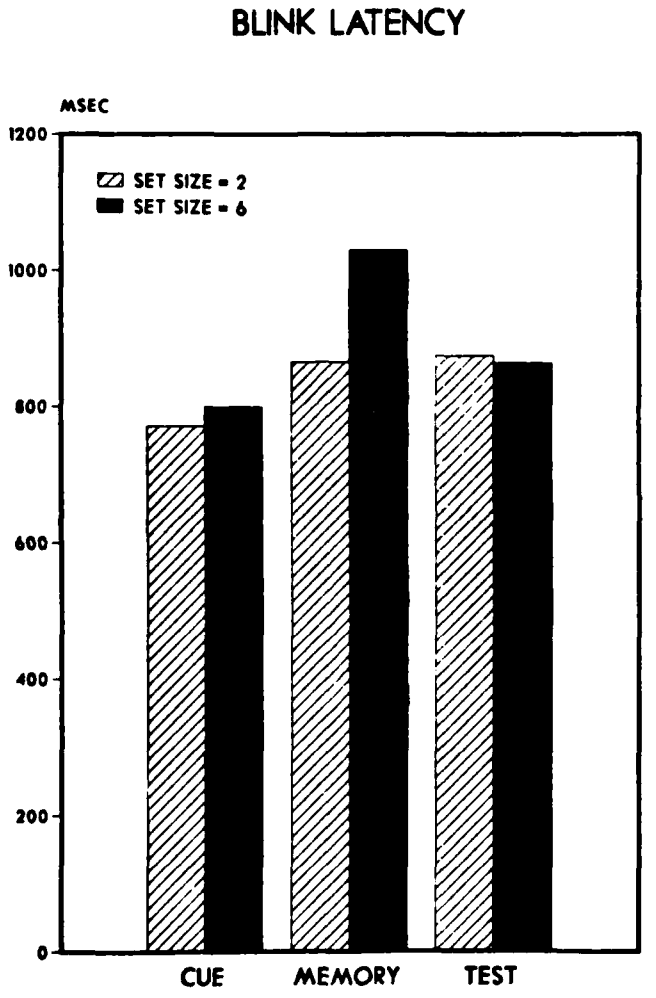

CUE PERIOD
MEMORY PERIOD
TEST PERIOD
BLINK RATE (BLINKS/MINUTE)
SHORT ISI, 2-ITEM
SHORT ISI, 6-ITEM
LONG ISI, 2-ITEM
LONG ISI, 6-ITEM
BIN NO.

Figure 2.6

Figure 2.7


BLINK LATENCY
MSEC
1200
1000
800
600
400
200
0
SET SIZE = 2
SET SIZE = 6
CUE
MEMORY
TEST

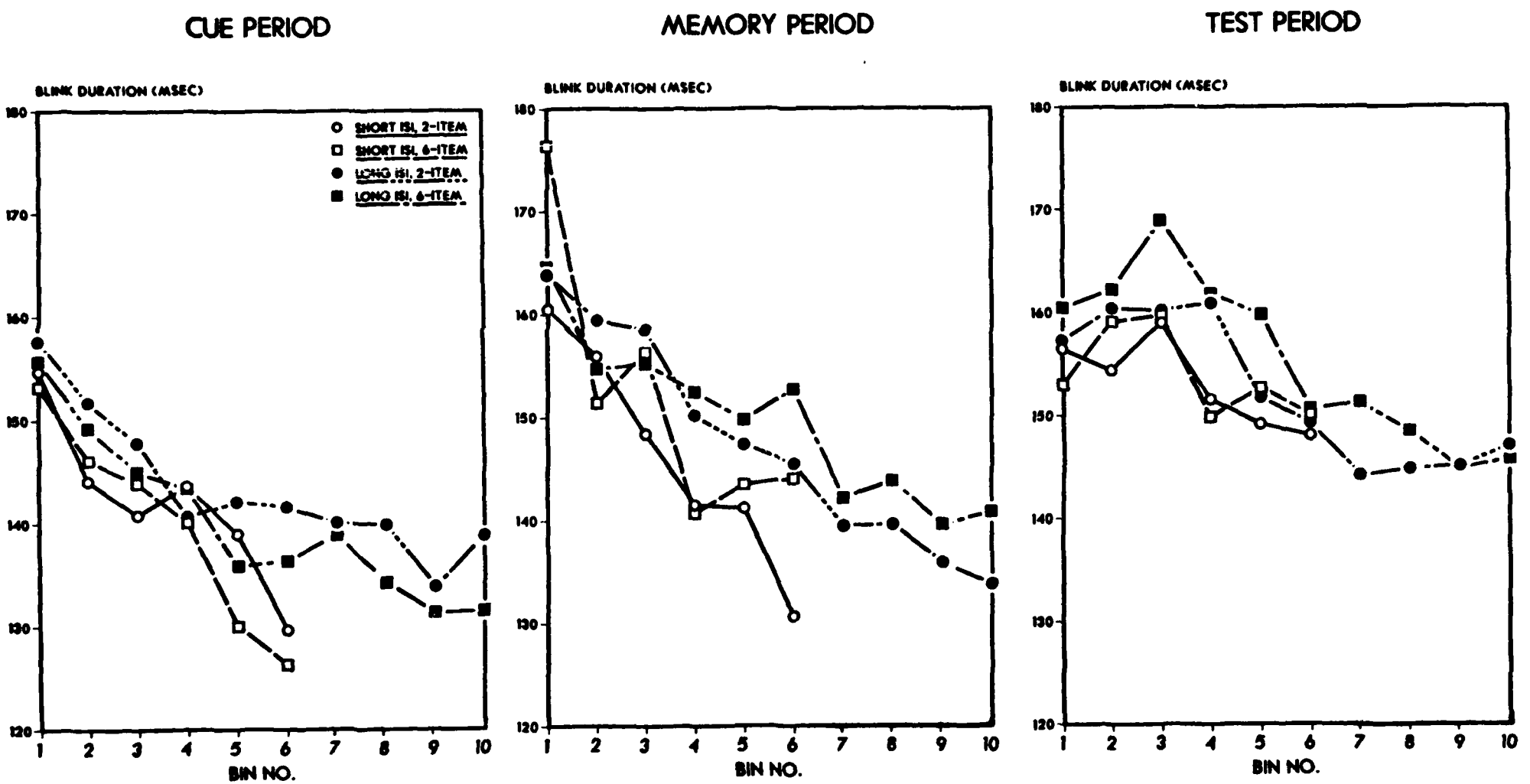

CUE PERIOD
MEMORY PERIOD
TEST PERIOD
BLINK DURATION (MSEC)
SHORT ISI, 2-ITEM
SHORT ISI, 6-ITEM
LONG ISI, 2-ITEM
LONG ISI, 6-ITEM
180
170
160
150
140
130
120
1 2 3 4 5 6 7 8 9 10
BIN NO.

Figure 2.8

Figure 2.9

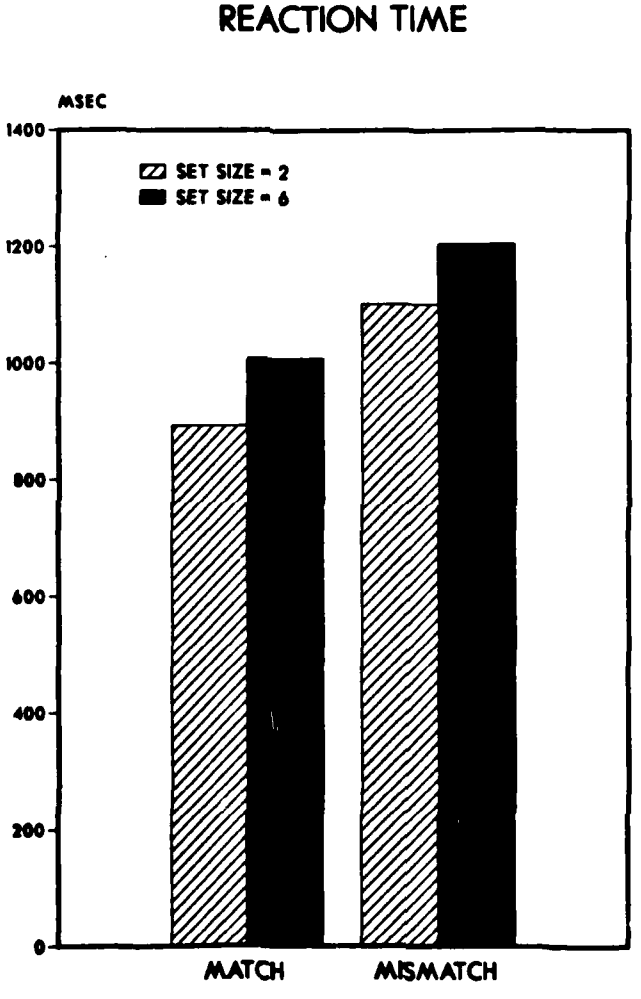
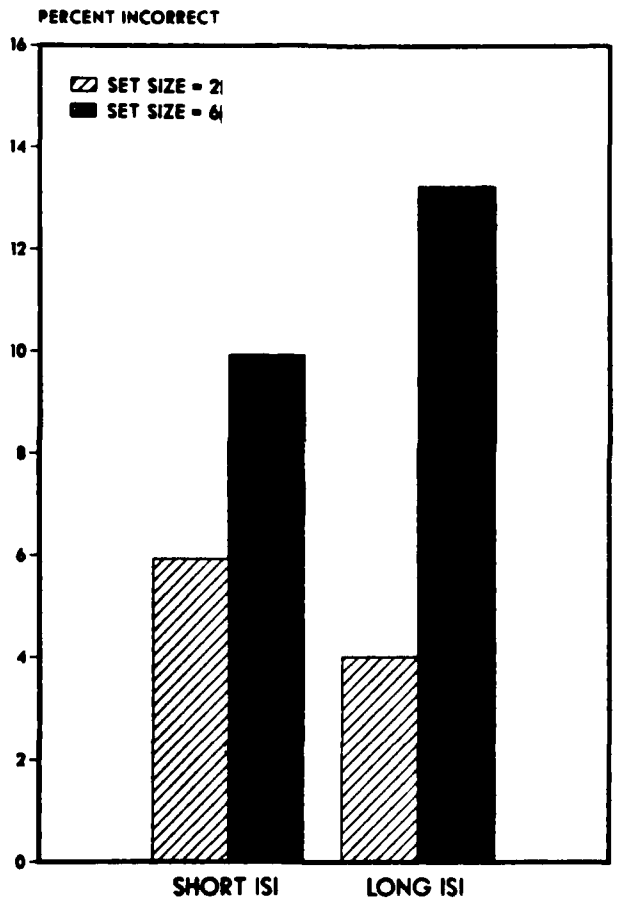

REACTION TIME
MSEC
1400
1200
1000
800
600
400
200
0
SET SIZE = 2
SET SIZE = 6
MATCH
MISMATCH

Figure 2.10


ERROR RATE
PERCENT INCORRECT
16
14
12
10
8
6
4
2
0
SET SIZE = 2
SET SIZE = 6
SHORT ISI
LONG ISI

STUDY 3

PROBE EVOKED POTENTIALS AND LATERALIZED COGNITIVE ACTIVITY: EFFECTS OF EXPECTANCY, AND PROCESSING DEMANDS.

INTRODUCTION

The elicitation of probe evoked potentials during tasks requiring predominantly verbal or nonverbal processing has served to document hemispheric asymmetries related to these two different processing modes. Several recent studies (e.g., Papanicolaou, Levin, Eisenberg, & Moore, 1983; Papanicolaou, Loring, & Eisenberg, 1985; Shucard, Cummins, Thomas, & Shucard, 1981; Thomas & Shucard, 1983) have shown that probe ERPs are attenuated in amplitude over the left hemisphere (LH) when subjects are asked to engage in verbal processing, and over the right hemisphere (RH) when they are asked to engage in nonverbal processing. Presumably, the attenuation of LH probe ERPs is related to concurrent verbal activity selectively limiting the availability of LH processing resources, whereas the attenuation of RH probe ERPs is related to concurrent nonverbal activity selectively limiting the availability of RH processing resources.

This hemisphere-specific attenuation of processing could be

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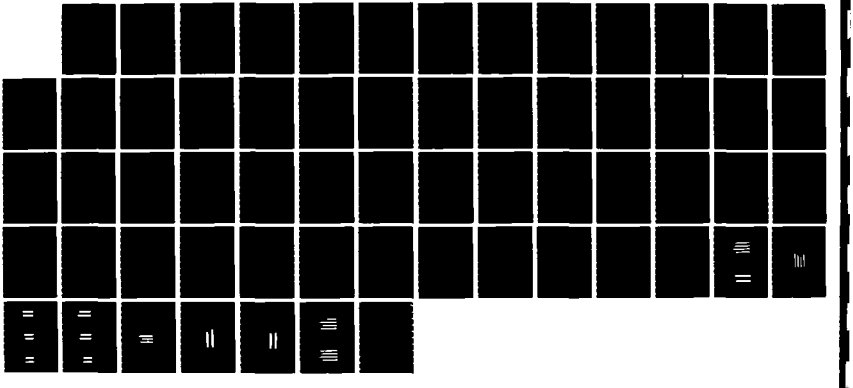
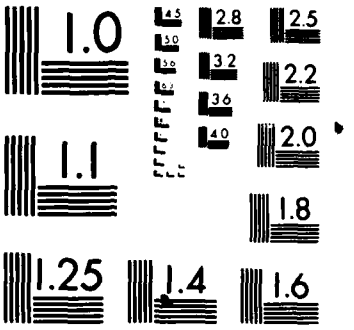
UNCLASSIFIED F49620-83-C-0059 F/G 5/10 NL





related to structural interference within the human information processing system, by which probe stimuli, occurring subsequent to the presentation of task relevant verbal or nonverbal stimuli, are provided only limited access to the hemisphere specialized for the processing of these stimuli. This type of explanation is based on Kimura's early work (1966, 1973) and on more recent work (for reviews, see Bradshaw & Nettleton, 1983; Bryden, 1982; Hellige, 1983) related to the specialized processing abilities of the left and right cerebral hemispheres.

Another mechanism for hemisphere-specific attenuation of the probe ERP is offered by an attentional model (Kinsbourne, 1970; Kinsbourne & Hicks, 1978). This model predicts that probe stimuli occurring prior to the presentation of task relevant verbal or nonverbal stimuli will elicit laterally asymmetric responses if the verbal/nonverbal nature of subsequent input is known and anticipated. Such expectation, by priming the appropriate hemisphere, is believed to affect the lateral distribution of attention in space and thereby favor the processing of stimuli presented in one sensory field over the other. This type of explanation is based on Kinsbourne's work on lateral gaze phenomena (see Gur & Gur, 1977, for a review) and on the effects of foreknowledge of the verbal/nonverbal nature of stimuli on the ear or visual field advantages they elicit (Cohen, 1975; Spellacy & Blumstein, 1970).

The relative contribution of structural and attentional factors to hemisphere-specific probe ERP attenuation can readily be explored with our current techniques. The present experiment sought to do so by manipulating, orthogonally, both the verbal/nonverbal nature of

the memory set and whether or not foreknowledge of this was provided. As before, probe stimuli were presented at fixed temporal positions preceding and following the memory set such that transient changes in probe ERP modification could be tracked. Unlike in our previous studies, however, the probe stimulus was spatially discrete and could occur in either the left or right visual field. This alloved the detection of covert shifts in the lateral distribution of visual atention occurring prior to the presentation of the task relevant stimuli.

Consistent with these views, it was hypothesized that:

(a). Increasing the number of items which comprise an ostensibly verbal memory set would, by loading the (language dominant) left hemisphere, selectively diminish the responsiveness of that hemisphere to task irrelevant visual stimulation in the interval following the memory set. In contrast, increasing the number of items which comprise an ostensibly nonverbal memory set was expected to diminish, selectively, the responsiveness of the right hemisphere.

(b). Foreknowledge of the verbal/nonverbal nature of a memory set, by priming the appropriate hemisphere, would affect the lateral distribution of attention in space in the interval preceding the memory set, relative to a condition in which foreknowledge was not provided. Specifically, the expectation of verbal processing was hypothesized to enhance the response evoked by right visual field probe stimuli, whereas the expectation of nonverbal processing was hypothesized to enhance the response evoked by left visual field probe stimuli (after Kinsbourne, 1970).

METHOD

Subjects

Thirteen undergraduate students participated in the experiment and were paid for their time. All were male, and their ages ranged between 18 and 29 years. They were all right-handed, as assessed with an abbreviated form of the Edinburgh Handedness Inventory (Oldfield, 1971), with no history of familial sinistrality. All had normal visual acuity, some with correction. They were all native speakers of the English language.

Apparatus

Stimulus delivery and timing were controlled by an LSI 11/23 computer. The task-relevant stimuli (i.e., the cue, memory set, and test stimuli) were produced by activation of an alphanumeric display unit (IEE, Inc., 1 x 80 Vacuum Flourescent Dot Matrix Display Module S03600-05-080) situated within a slot cut in the center of a vertically-oriented, 1.14 m (length) x 0.6 m (height) plywood board. The probe stimuli were produced by activation (duration = 50 ms, luminance = 20.52 cd/m**2) of one of two sets of nine 7 watt miniature incandescent bulbs, arranged in square matrices (0.8 deg x 0.8 deg), mounted 6 deg to the left and right of center.

The subject sat inside a 2.3 m x 2.7 m, sound-attenuated, electrically-shielded room (ambient light intensity = 0.3 lx) facing the center of the dot matrix display. His head was held stationary by a chinrest anchored to the arms of the chair. A response panel consisting of two buttons, positioned 2 cm to either side of the midline axis, was placed in front of the subject.

Two measures of physiological activity were recorded in the present investigation. Electroencephalographic (EEG) activity was recorded with Grass silver/silver chloride electrodes from four lateral scalp sites: P3, P4, T3, and T4 (according to the International 10/20 System, Jasper, 1958). All EEG channels were referred to linked earclips. Vertical electro-oculographic (vEOG) activity was recorded bipolarly between Beckman miniature biopotential electrodes placed above and below the left eye. An electrode taped to the center of the subject's forehead served as ground. Inter-electrode impedances were kept below 5 Kilohms.

The EEG signals were amplified and filtered by Grass Instrument Co. amplifiers (model 7P1, gain = 20K, nominal bandpass = 0.1 to 35 Hz). The EOG signal was amplified by a specially constructed amplifier (gain = 3K, bandpass = DC to 200 Hz). Each of these physiological signals, along with a response event marker, were stored in digital form (sampling rate = 200 Hz) on computer disk for off-line analysis.

Stimuli

The cue stimulus was comprised of a set of 4 characters projected (retinal angle subtended = 0.5 deg x 0.2 deg high, average luminance/character = 25.99 cd/m**2) for 1 sec from the center of the dot matrix display. The leftmost character of the cue stimulus was the letter 's' or the letter 'l', indicating to the subject that a small or large memory set would follow. The rightmost three characters of the cue stimulus were the letter strings 'eng', 'jap', or 'non'. These indicated, respectively, that a memory set consisting of English characters, Japanese (Katakana) characters, or

that a set comprised of either English or Japanese characters would follow.

The memory set and test stimuli were presented for the same duration and centered at the same location as the cue stimulus. The characters comprising the English character memory sets and test stimuli were selected at random, without replacement, from a set of 14 consonant, lower case letters The characters comprising the Japanese character memory sets and test stimuli were selected from a set of 10 simply-structured Katakana characters. The memory set and test stimuli were arranged in a stimulus series with the following restrictions: that in each sequence of 140 trials, each set size and type of memory set occurred equally often, the test stimulus was a member of the memory set on one-half of the trials, and on such trials it occurred with equal frequency at each position in the memory set.

As it was of some theoretical importance to equate the memory loads imposed by the English and Japanese character memory sets at each level of task difficulty, a pilot study was conducted for the purpose of selecting numbers of English and Japanese characters which, when presented in a memory set, would yield comparable recognition accuracies on later testing. This work established that memorization of 2- and 6-item English character memory sets yielded recognition accuracies roughly equivalent to those yielded by memorization of 1- and 2-item Japanese character memory sets, respectively. These set sizes were employed in the present investigation. To alleviate confusion in future discussions, set size will hereafter be indexed by the labels "small" and "large", and

not by the absolute number of items comprising the English and Japanese character memory sets.

Procedure

Subjects were tested on 2 days at approximately the same clock time. Each experimental day was divided into 5 trial blocks. The first was a 3 min block consisting of 15 practice trials. This was followed by four 15 min blocks consisting of 70 trials each, separated by 2-3 min rest periods.

Each trial, as diagrammed in Figure 3.1, consisted of a cue stimulus, a memory set, and a test stimulus, in sequence. On

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Insert Figure 3.1 about here

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every trial, a probe stimulus was presented at two of four possible temporal locations in the 2000 ms interval following the cue stimulus (i.e., at 400 or 700 ms and at 1300 or 1600 ms following cue stimulus offset) and at three of nine possible temporal locations in the 5000 ms interval following the memory set (i.e., at 500, 800 or 1100 ms, at 2200, 2500, or 2800 ms, and at 3900, 4200, or 4500 ms following memory set offset). The visual field in which the probe occurred (i.e., right or left) was varied randomly.

Prior to the experiment proper, subjects received written instructions which emphasized the need to restrict movement and to maintain fixation on a fixation cross situated just below the center of the dot matrix display. The instructions explicitly pointed out the relevance and timing of the cue, memory set, and test stimuli. Specifically, subjects were told that, on every trial, the cue

stimulus would accurately inform them of the relative size of the ensuing memory set and, on one-half of the trials, the nature of the items contained therein (i.e., English or Japanese characters). Subjects were instructed to use the information contained in the cue stimulus to their best advantage. Subjects were further instructed that when the memory set appeared, 3 sec later, they were to encode and silently retain the items until the test item was presented. At that time, they were to execute a speeded reaction time (RT) response, indicating whether or not the test item was a member of the set. For seven of the subjects, this meant that they were to press the right response button with the right index finger if the test item was a member of the memory set (a "match" response), and the left button with the left index finger if it was not (a "mismatch" response). For the remaining six subjects, this was reversed.

Data Reduction

Event-Related Potentials. The EEG and EOG signals were digitized on-line (rate = 200 Hz) and were digitally filtered off-line (0 db at 30 Hz, -3 db at 33 Hz, -6 db at 45 Hz) prior to analysis. In order to exclude from analysis any ERPs that might be contaminated by eye movement, lead sway, or muscle artifacts, EEG epochs for stimuli on which the range in either the EOG or EEG exceeded preset criteria (viz., 50 and 100 uV, respectively) were rejected. Any trials with missing behavioral responses were also rejected. Remaining epochs of EEG from 100 ms preceding to 500 ms following stimulus onset were retained. For each subject, these data were combined into time-point averages, temporally locked to the stimuli. The averages were computed separately for P3, P4, T3, and T4 leads. For the cue and

memory set ERPs, averages were further sorted by set size (small/large), memory set character type (English/Japanese), and cue condition (character type cued/character type uncued). For the ERPs elicited by test stimuli, averages were also sorted by the membership, or lack thereof, of the eliciting stimulus in the memory set (i.e., match/mismatch).

Probe stimulus ERPs were sorted in a different manner. Those elicited during the cue interval were sorted by set size (small/large), memory set character type (English/Japanese), cue condition (character type cued/character type uncued), temporal position (early/late), recording lead (P3/P4/T3/T4), and visual field (RVF/LVF). Probe ERPs elicited during the memory interval were sorted by set size (small/large), memory set character type (English/Japanese), cue condition (cued/uncued), temporal position (early/middle/late), recording lead (P3/P4/T3/T4), and visual field (RVF/LVF).

The factorial combination of experimental conditions and recording derivations yielded a total of 448 ERPs per subject, each formed by an average of at least 25 trials. In each of the ERPs, five components were visually identified and measured. The cue, memory set, test, and probe ERPs were characterized by a complex of 5 alternate positive- and negative-going waves occurring within latency ranges of 65-90, 90-120, 120-170, 170-220, 220-350 ms post-onset. The maximum or minimum voltage of the averaged ERP within each of these windows was determined to be the amplitude, with respect to the average voltage of the EEG in a 100 ms period preceding stimulus onset, of P1, N1, P2, N2, and P3, respectively.

Since probe ERPs were typically superimposed on a changing baseline, i.e., a contingent negative variation or CNV (for a review, see Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982), their component amplitudes were expressed in terms of the amplitude difference between adjacent positive and negative peaks. This transformation served to minimize the potentially confounding effect on probe ERP component amplitudes of slowly developing waves, such as CNVs, which might also be affected by the variables of interest. The validity of this assumption was tested by including the baseline voltage of the probe ERP in the analysis as an estimate of CNV amplitude.

Performance. The response signal event marker was digitized on-line and later subjected to analysis. Using this marker, the latencies of correct responses were calculated from test stimulus onset, and were sorted by set size, memory set character type, cue condition, and membership. The median RT within each trial category was taken as the measure of central tendency. The proportion of trials on which the subject responded inappropriately was also calculated from these data and sorted in the same manner. Prior to analysis, the reaction time and error rate data were subjected to log- and arcsine transformation, respectively.

RESULTS

ERP Data

Due to the size of the data sets and limitations on the availability of computer memory, separate analyses of ERP data sampled from parietal and temporal sites were required. Results from the analysis of the cue and memory set ERPs, the test ERP (Figure

3.2), and the cue interval and memory interval probe ERPs (Figure 3.3), at each of these derivations, will be presented separately.

Insert Figures 3.2 and 3.3 about here

The analytic procedure in every case was a multivariate ANOVA (MANOVA). Univariate analyses are reported only when the test for that variable was significant in the overall MANOVA. The degrees of freedom for these analyses were adjusted, where appropriate, using the conservative Geisser-Greenhouse (1958) procedure. Adjusted df's are reported.

Task ERPs

As noted previously, the cue and memory ERPs were sorted, for analysis, by the factorial combination of the stimulus type (cue / memory set), hemisphere (LH/RH), set size (small/large), memory set character type (Japanese/English), and cueing (character type cued / character type uncued) factors. Sorting of the test stimulus ERP omitted the stimulus type factor and included one additional factor, viz., membership (match/mismatch). The results of the analysis of the cue and memory set ERPs will be presented first.

Cue and Memory Stimulus ERPs

Parietal Derivations. Table 1 presents the average amplitudes, in microvolts, of the P1, N1, P2, N2, and P3 components elicited by the cue and memory set stimuli. The results of the analysis of these data are summarized in Table 2.

Table 1

Average Amplitudes of Cue and Memory Set ERP Components

	P1	N1	P2	N2	P3
Cue	1.92	0.27	6.06	4.30	6.97
Memory Set	1.41	-0.25	5.43	4.28	8.08

The MANOVA yielded significant main effects for set size ($F(5,8)=5.1$, $p<0.03$), cueing ($F(5,8)=4.0$, $p<0.04$), and stimulus type ($F(5,8)=6.1$, $p<0.02$), as well as several significant interactions. Univariate analyses following up the significant set size main effect revealed that N2 was smaller ($F(1,12)=10.9$, $p<0.01$) and P3 was larger ($F(1,12)=15.4$, $p<0.01$) for large than small memory set size trials. The significant stimulus type by set size interaction (Manova $F(5,8)=4.1$, $p<0.05$; N2: $F(1,12)=4.7$, $p<0.05$; P3: $F(1,12)=15.3$, $p<0.01$) indicates that the enhancing effect of set size was restricted to the memory set ERP. This interpretation was borne out by the results of post hoc tests (Tukey, alpha=0.05) of the effects of set size for each level of the stimulus type variable.

The main effect found for cueing indicates that foreknowledge of the type of characters comprising the memory set was associated with a smaller P3 ($F(1,12)=21.3$, $p<0.001$) than when foreknowledge was not provided. The interpretation of this main effect is, however, qualified by the presence of statistically significant stimulus type by cueing (Manova $F(5,8)=4.4$, $p<0.04$) and stimulus type by cueing by set size (Manova $F(5,8)=11.2$, $p<0.002$) interactions which also involved the P3 component (Univariate tests: $F(1,12)=15.6$, $p<0.002$

and $F(1,12)=18.9$, $p<0.001$, for the two and three way interactions, respectively). Post hoc tests of the effect of cueing for each combination of the levels of the stimulus type and set size variables revealed that uncertainty with regard to the type of characters comprising the memory set enhanced the P3 to that memory set only when demands were at their greatest (Table 3), i.e., on large set size trials. Cueing had no effect on cue stimulus ERP P3 amplitude or on memory set ERP P3 amplitude for small set size trials.

Table 3

Average P3 Amplitude (in uV)

	Cue ERP	Memory Set ERP
Small		
Cued	6.7	6.7
Uncued	7.0	7.3
Large		
Cued	7.2	7.5
Uncued	6.8	10.7

The third significant main effect in this analysis was that of stimulus type (Table 1). Univariate analyses revealed that three components discriminated between the cue and memory stimulus ERPs, viz., P1 ($F(1,12)=9.2$, $p<0.02$), P2 ($F(1,12)=11.8$, $p<0.01$), and P3 ($F(1,12)=14.7$, $p<0.005$). In the case of the P1 and P2 components, amplitudes were generally larger in the cue ERP than in the memory ERP. For P3 amplitude, the direction of this effect was reversed.

Of particular relevance to our stated hypotheses are the

significant hemisphere x character type x stimulus (Manova $F(5,8)=5.1$, $p<0.05$) and hemisphere x character type x stimulus x cueing (Manova $F(5,8)=3.8$, $p<0.05$) interactions involving the P2 component ($F(1,12)=5.9$, $p<0.04$, and $F(1,12)=7.4$, $p<0.02$, for the three and four way interactions, respectively). The left panel of

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Insert Figure 3.4 about here

Figure 3.4 depicts an interesting and complex relationship among the levels of the hemisphere and character type variables (restricted to the memory set ERP) by which English character memory sets elicited a larger P2 component than Japanese character memory sets over the left hemisphere, while, over the right hemisphere, the direction of this effect was reversed. The interaction of cueing, hemisphere, and character type, illustrated in the right panel of Figure 3.4, suggests that foreknowledge of the type of characters comprising the memory set was essential to this pattern of results. Comparisons (Tukey, alpha=0.05) of P2 amplitudes elicited by English and Japanese character memory sets for each combination of the levels of the other variables verified this interpretation.

The other significant result in this analysis was the five way interaction of stimulus x character type x hemisphere x set size x cueing (Manova $F(5,8)=3.7$, $p<0.05$) involving P2 ($F(1,12)=18.3$, $p<0.002$). No combination of post hoc tests made this result interpretable, however.

Temporal Derivations. The analysis of cue and memory ERP data, derived from temporal sites, yielded fewer significant results than

the analysis of ERP data derived from parietal sites. The results of these analyses are summarized in the right panel of Table 2.

The significant results in this analysis were a main effect for cueing (Manova $F(5,8)=7.3$, $p<0.01$), and the interactions of stimulus type x set size (Manova $F(5,8)=4.2$, $p<0.05$, stimulus type x cueing (Manova $F(5,8)=4.3$, $p<0.04$), and stimulus type x set size x cueing (Manova $F(5,8)=9.4$, $p<0.01$). These effects involved the same component, viz., P3, and were in the same direction as their counterparts in the analysis of the parietal data.

Test Stimulus ERPs

Parietal Derivations. The results of this analysis are summarized in Table 4.

As was the result in the analysis of the memory set ERP, the analysis of the test stimulus ERP revealed no significant influence of set size on P1, N1, or P2 amplitudes. With respect to the amplitude of P3, however, a highly reliable main effect of set size (Manova $F(5,8)=6.8$, $p<0.0002$; Univariate $F(1,12)=105.2$, $p<0.00001$) as well as a significant interaction of character type x set size (Manova $F(5,8)=11.3$, $p<0.01$; Univariate $F(1,12)=8.63$, $p<0.02$) were found. Table 5 shows that while P3 amplitude was, in general, inversely related to set size, this was especially true when the stimulus invoking the P3 was a Japanese character.

Table 5

Average P3 Amplitude (in uV)

	English	Japanese
Small	6.4	8.3
Large	5.5	5.7

The only other significant results in this analysis were a main effect of character type (Manova $F(5,8)=6.8$, $p<0.01$), for the N1 ($F(1,12)=10.1$, $p<0.01$) and P3 ($F(1,12)=6.4$, $p<0.03$) components, and the interaction of hemisphere x set size x membership (Manova $F(5,8)=3.7$, $p<0.05$) for N2 ($F(1,12)=13.5$, $p<0.05$). The former effect indicates that N1 was more negative and P3 more positive to Japanese than to English character test stimuli. The hemisphere x set size x membership effect, which is illustrated in Figure 3.5, indicates that

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Insert Figure 3.5 about here

N2 recorded over the right hemisphere varied as a function of the number of items with which the stimulus eliciting the N2 was to be compared. This effect was restricted to those instances when the test stimulus was a member of the memory set. There were no corresponding effects on the N2 recorded over the left hemisphere. Post-hoc tests (Tukey, alpha=0.05) verified this interpretation.

Temporal Derivations. The main effects of set size (Manova $F(5,8)=8.5$, $p<0.01$) and character type (Manova $F(5,8)=4.8$, $p<0.03$), and the joint effect of set size x character type (Manova $F(5,8)=4.3$,

$p<0.04$) found in the analysis of the parietal data were replicated in the analysis of the temporal data (Table 4). These effects did not involve the same components in every instance, however. Here, in addition to P3 ($F(1,12)=53.4$, $p<0.00001$), the amplitudes of the P2 ($F1,12)=4.8$, $p<0.05$) and N2 ($F(1,12)=6.9$, $p<0.03$) components were inversely related to set size, i.e., all were *less* positive on large, as compared to small, memory set size trials. Further, in this analysis, N2 amplitude discriminated character types ($F(1,12)=13.6$, $p<0.005$), being more positive for Japanese than English character test stimuli. The character type x set size interaction involved the same component, viz., P3 ($F(1,12)=12.1$, $p<0.01$), and was in the same direction as noted previously.

Probe ERPs

The primary question addressed in this study was the extent to which ERPs elicited by simple visual probe stimuli would change their lateral distribution depending on whether the subject was anticipating or retaining ostensibly verbal or nonverbal memory sets of varying sizes. Tables 6 and 7 present the results of the analyses of these data. Quite obviously, not all of our stated hypotheses were confirmed. A detailed description of the results follows.

Cue Interval Probe ERPs

Parietal Derivations. Probe ERPs and the CNV were measured at two temporal positions in the cue interval, viz., at 400-700 ms and at 1300-1600 ms following cue stimulus offset. At the late probe position (Manova $F(5,8)=5.0$, $p<0.03$), N1-P2 was greater than it was at the early probe position ($F(1,12)=8.5$, $p<0.02$). The amplitude of the CNV also changed over probe positions ($F(1,12)=4.3$, $p<0.001$),

being less negative at the late probe postion than at the early probe position. Neither CNV amplitude nor probe ERP component amplitudes varied systematically with the size of the anticipated memory set.

The MANOVA also indicated (Manova $F(5,8)=17.9$, $p<0.005$) that N1-P2 ($F(1,12)=5.5$, $p<0.04$), P2-N2 ($F(1,12)=7.8$, $p<0.02$), and N2-P3 ($F(1,12)=6.3$, $p<0.03$) amplitudes changed their scalp distribution depending on whether the probe stimulus occurred in the right or left visual field (Table 8). The scalp distribution of these components was not found to vary as a function of the anticipated character type, nor as a function of whether or not foreknowledge of character type was provided.

The only other significant factor in this analysis was that of hemisphere (Manova $F(5,8)=93.4$, $p<0.001$). Univariate tests attributed this to CNV amplitude ($F(1,12)=434.2$, $p<0.001$), which was more negative over the RH than the LH.

Table 8

N1-P2, P2-N2, and N2-P3 Amplitudes (in uV)

	LVF		RVF	
	LH	RH	LH	RH
N1-P2	2.3	3.4	3.0	3.7
P2-N2	1.5	1.9	1.8	1.7
N2-P3	1.8	1.8	1.6	2.0

Temporal Derivations. In this analysis, the hemisphere factor again significantly (Manova $F(5,8)=64.4$, $p<0.0001$) affected the amplitude of the CNV ($F(1,12)=277.97$, $p<0.00001$). The direction of the effect was the same as reported previously. The visual field x cueing interaction was also significant (Manova $F(5,8)=5.4$, $p<0.02$) for P1-N1 ($F(1,12)=10.1$, $p<0.01$) in this analysis. That is, when the type of characters comprising the memory set remained uncertain, RVF probes elicited larger N1-P2 responses than LVF probes. When uncertainty was reduced by the cue, however, no VF asymmetry in the response to the probe was found.

Several isolated and uninterpretable higher order interactions also reached significance. Since some of these produced changes in the composite dependent variable (i.e., the variable tested by the MANOVA), but not in any one dependent variable, and others were not readily interpretable in terms of the purposes of the present experiment, they will not be discussed.

Memory Interval Probe ERPs

Parietal Derivations. Probe ERPs were elicited at three temporal positions during the memory interval, viz., at 500-1100 ms, at 2200-2800 ms, and at 3900-4500 ms following offset of the memory set stimulus. Tests of both the probe position main effect (Manova $F(10,40)=4.4$, $p<0.001$) and the probe position x visual field x hemisphere interaction (Manova $F(10,40)=2.4$, $p<0.03$) revealed significant changes in probe ERP component amplitudes as the memory interval progressed. This claim is supported by the increase demonstrated in the amplitude of two early probe ERP components,

viz., P1-N1 ($F(1,16)=9.2$, $p<0.005$) and N1-P2 ($F(1,16)=15.3$, $p<0.001$), and by the decrease in the amplitude of a later component, viz., P2-N2 ($F(1,14)=4.5$, $p<0.05$), across probe positions. Also suggesting an alteration of responsiveness over time is the stabilization of the "directness of pathway" effect (i.e., the VF x hemisphere interaction) over probe positions manifest in the significant VF x hemisphere x probe position interaction for N1-P2 ($F(2,21)= 5.8$, $p<0.02$) illustrated in Figure 3.6. Such a pattern of results is indicative of a narrowing attentional focus over time.

A third effect involving the probe position factor was the significant VF x character type x probe position interaction (Figure 3.7) (Manova $F(10,40)=2.5$, $p<0.03$) for P2-N2 ($F(2,24)=4.3$, $p<0.03$)

Insert Figures 3.6 and 3.7 about here

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and N2-P3 ($F(2,22)=3.5$, $p<0.05$). Tests of the VF x character type interaction conducted separately for each probe position attribute this effect to changes in the probe ERP elicited at the middle probe position exclusively. At this moment in the trial, RVF probes were found to elicit smaller responses than LVF probes if the interval was preceded by an English character memory set, and LVF probes were found to elicit smaller responses than RVF probes if the interval was preceded by a Japanese character memory set. Paradoxically, this pattern of results was not also reflected in the N2-P3 responses recorded over the left and right hemispheres. That is, the reduced N2-P3 response to RVF probes was not apparent in a reduced N2-P3 response over the LH, and, conversely, the reduced N2-P3 response to

LVF probes was not apparent in a reduced N2-P3 response over the RH.

The only other significant results of this analysis were an interaction of set size and probe position (Table 9) (Manova $F(10,40)=2.3$, $p<0.01$) and a main effect for hemisphere (Manova $F(5,8)=90.6$, $p<0.001$) both involving CNV amplitude ($F(10,40)=7.5$, $p<0.04$; and $F(1,12)=421.8$, $p<0.0001$, respectively).

Table 9

CNV Amplitude (arbitrary units)

	Early	Middle	Late
Small	403.40	403.03	403.51
Large	402.79	403.79	404.13

Temporal Derivations. The center panel of Figure 3.8 presents probe ERP N2-P3 amplitude for each of the two memory set sizes at each

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Insert Figure 3.8 about here

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probe position in the memory interval. It is quite evident that the effect of memory set size on N2-P3 changed as a function of probe position (Manova $F(10,40)=2.1$, $p<0.05$; Univariate $F(2,24)=5.5$, $p<0.02$). Post hoc tests indicate that the set size effect was significant at the middle probe position only.

Several other results attained significance. The visual field x hemisphere interaction (Figure 3.9) was significant (Manova $F(5,8)=9.9$, $p<0.01$) for P1-N1 ($F(1,12)=11.0$, $p<0.01$), and, in addition, the VF x character type interaction (Figure 3.10) was significant (Manova $F(5,8)=5.6$, $p<0.02$) for N1-P2 ($F(1,12)=11.5$, $p<0.005$). The former effect indicates that RVF probes elicited

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Insert Figures 3.9 and 3.10 about here

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larger P1-N1 responses over the LH than LVF probes, and, conversely, that LVF probes elicited larger P1-N1 responses over the RH than RVF probes. The significant VF x character type interaction indicates that N1-P2 responses to LVF probes were larger on trials requiring the retention of Japanese character memory sets than on those requiring retention of English character memory sets.

The 5 way interactions of VF x hemisphere x set size x character type x cueing (Manova $F(5,8)=4.7$, $p<0.04$) and VF x probe position x character type x set size x cueing (Manova $F(10,40)=2.4$, $p<0.05$) were significant for P1-N1 ($F(1,12)=6.1$, $p<0.01$) and for N1-P2 ($F(1,16)=5.5$, $p<0.05$), respectively. These effects belie interpretation.

The only remaining effects to be presented here are the main effects for hemisphere (Manova $F(5,8)=46.2$, $p<0.01$) and probe position (Manova $F(10,40)= 5.9$, $p<0.01$). Univariate tests following up the hemisphere and probe position main effects revealed that, again, CNV amplitude was found to be greater over the right than the left hemisphere ($F(1,12)=281.3$, $p<0.0001$) and that P1-N1 amplitude increased over probe positions ($F(1.9,23.3)=6.3$, $p<0.01$).

Performance Data

Reaction time and error data are illustrated in Figure 3.11. A four way MANOVA with all factors within (set size x memory set

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Insert Figure 3.11 about here

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character type x membership x cue condition) yielded two significant main effects. Set size reached significance (Manova $F(2,12)=24.25, p<0.001$), and, in addition, membership was significant (Manova $F(2,12)=11.14, p<0.01$). Univariate analyses of variance indicated that the set size effect resulted from both reaction time and error rates being relatively greater on large than small memory set size trials (RT: $F(1,13)=48.90, p<0.0001$; Error Rate: $F(1,13)=25.13, p<0.001$). Univariate analyses following up the significant membership effect revealed that it was attributable, solely, to variation in the reaction time measure ($F(1,13)=12.33, p<0.01$). Examination of the RT data plotted in Figure 11 reveals that correct "different" judgments took longer, on the average, than correct "same" judgments.

Two interactions also yielded significant results: the set size x membership (Manova $F(2,12)=5.47, p<0.02$) and the set size x membership x character type (Manova $F(2,12)=4.13, p<0.05$) interactions. Subsequent analyses employing univariate analyses of variance and post hoc (Tukey, alpha=0.05) tests indicated that RT varied with set size on match, but not on mismatch, trials ($F(1,13)=6.13, p<0.03$). This pattern of results was mirrored in the error data ($F(1,13)=7.66, p<0.02$), although the interactive effects of set size and membership on error rate were restricted to trials on which subjects compared Japanese test stimuli to Japanese character memory sets ($F(1,13)=6.18, p<0.03$).

Summary of Results

The significant effects in this study were the following:

1. Expectancy (Cueing). A significant reduction in memory set ERP P3 amplitude was imparted by foreknowledge of memory set character type. This is compatible with a large body of research suggesting that expected events elicit smaller P3's than unexpected events (Donchin, 1981).

Foreknowledge of character type also affected the lateral distribution of the ERPs evoked by the memory set and cue interval probe stimuli. In the analysis of the memory set ERP, it was found that foreknowledge of character type enhanced the P2 elicited by English character memory sets (relative to the P2 elicited by Japanese character memory sets) over the left hemisphere, and the P2 elicited by Japanese character memory sets (relative to the P2 elicited by English character memory sets) over the right hemisphere. When character type was uncued, however, no asymmetries in the P2 response to English or Japanese character memory sets were found.

Although cueing of memory set character type yielded a laterally asymmetric response to the memory set, cueing did not also yield an asymmetric response to RVF and LVF probe stimuli in the interval preceding the memory set. It was only when the type of characters comprising the memory set remained uncertain that evidence for an asymmetry was found. This involved the N1-P2 component.

2. Processing demands (Set Size). Consistent with the findings of O'Boyle and Hellige (1982) and others, increasing the number of items which comprised ostensibly verbal or nonverbal memory sets had no effect on the laterally-represented encoding mechanisms they are

presumed to engage differentially. In this study, increased processing demands were shown to load a cognitive process, indexed by P3, which appears to be symmetrically represented. Accordingly, set size was shown to increase the amplitude of the P3 evoked by the memory set and to decrease the amplitude of the P3 and the N2-P3 evoked by the test and memory interval probe stimuli, irrespective of the hemisphere over which these components were recorded.

In contrast to the P3 results which showed no differentiation in amplitude between the hemispheres as a function of set size, test stimulus ERP N2 amplitude was found to increase with set size, on match trials, over the RH, but not on mismatch trials, or over the LH. Consistent with the N2 results, both reaction time and error rate were found to increase with set size on match, but not on mismatch, trials. The reaction time and error data are consistent with a large body of research that commenced with Sternberg (1966).

3. Time (Probe Position). Evidence suggestive of a gradual and differential engagement of left and right hemisphere short term memory processes was provided by the finding of a laterally asymmetric N2-P3 response to RVF and LVF probes in the memory interval which varied with probe position and memory set character type. Specifically, a diminished N2-P3 response to RVF probe stimuli was apparent at 2.2 to 2.8 sec (i.e., at the middle probe position) following the presentation of an English character memory set, whereas a diminished N2-P3 response to LVF probe stimuli was apparent at 2.2 to 2.8 sec following the presentation of a Japanese character memory set. These effects were not apparent at any other time in the interval, i.e., at neither the early nor the late probe positions.

4. Miscellany. The formidable number of conditions used in this experiment gave rise to a number of statistically significant, but theoretically trivial, results. Most notable among these were the following:

(a) CNV amplitude, measured in the cue and memory intervals, was uniformly larger over the right hemisphere than over the left hemisphere. The simplest explanation which can be offered for this result derives from the finding that, for most individuals, the right hemisphere has more tissue than the LH and it is protected by a relatively thinner cranium (LeMay, 1976). Both of these morphological asymmetries would favor the amplitudes of RH responses.

(b) Japanese character test stimuli elicited larger amplitude N1 and P3 responses than English character test stimuli. The direction of this effect, and the documented sensitivity of the components affected to increased attentional demands, leads to the rather obvious conclusion that the processing of unfamiliar stimuli (e.g., Japanese characters) is more demanding of attention than the processing of familiar stimuli (e.g., English characters).

(c) Probe ERP P1-N1 and N1-P2 amplitudes, recorded over the right and left cerebral hemispheres, were markedly larger under conditions of direct, as compared to indirect, stimulation (cf. Andreassi, Okamura, & Stern, 1975). This result, combined with the lack of such an interaction at the probe position immediately following the memory set (Figure 3.6), adds further weight to our suggestion that an important determining factor of asymmetries in the ERPs elicited by neutral visual stimuli presented in the right and left visual fields is the background against which these ERPs are

elicited; asymmetries do not necessarily follow as a result of divided visual field stimulation.

Since these and many of our other findings have been demonstrated repeatedly in the past, and are not the subject of heated debate, they will not be discussed further. Consideration will instead be given to those aspects of the present results that are informative with respect to cerebral hemisphere asymmetry or that are the subject of some controversy.

DISCUSSION

The pattern of lateral asymmetries observed in the memory set ERP (Figure 3.4) as a function of cueing and the type of characters comprising the memory set was striking and in line with our predictions. On the other hand, and contrary to our predictions, the contribution of increased processing demands to these lateral asymmetries appeared unsystematic and genuinely insignificant. The results showed that when character type was cued, English character memory sets elicited larger P2 amplitudes over the left hemisphere than Japanese character memory sets, and Japanese character memory sets elicited larger P2 amplitudes over the right hemisphere than English character memory sets; when character type was not cued, no lateral asymmetries were observed.

To what model do these findings conform? A visuo-spatial frequency model (Sergent, 1982a, 1982b, 1982c, 1983a,b, 1985), which would attribute the differing laterally-asymmetric responses to the Japanese and English character memory sets to presumed differences in the physical characteristics of these memory sets, cannot account for the findings. An examination of the Japanese and English characters

(Appendix A) used to construct the memory sets reveals no obvious differences in terms of their visual complexity. Even if there were differences, however, a visuo-spatial frequency model would predict a stable hemisphere advantage across expectancy conditions. This was clearly not the case

If the observed hemisphere differences in the memory set ERP were due to inherent differences in the difficulty of encoding the Japanese and English character memory sets, and not to differences in the manner by which these were encoded, then one might have expected that the encoding of a large memory set would yield a RH advantage, and a small memory set, a LH advantage, regardless of character type. Yet this was also found not to be the case. Further evidence disputing the speculation that memory sets composed of Japanese characters were any more difficult to encode than their English counterparts is provided by the absence of a character type main effect on the memory set ERP and on the probe ERPs elicited subsquent to it. These negative results verify that the attempt made to equate the loads imposed by the Japanese and English sets was successful.

To what mechanism, then, should the different responses elicited by the Japanese and English memory sets, and the dependence of this difference in cueing, be attributed? Several experiments have been mentioned earlier (e.g., Cohen, 1975; Spellacy & Blumstein, 1970) that support the contention that foreknowledge of the type of stimulus to be presented can prime the appropriate hemisphere so that, for example, a LH superiority for words and letters is more marked if verbal stimuli are expected, i.e., a verbal "set" has been formed. How this improvement is achieved is not clear. Expectancy for

a particular type of stimulus may allow preselection of an appropriate encoding strategy, such as the detection of certain critical features or covert naming, which are asymmetrically represented. Or it may increase processing capacity by globally arousing the hemisphere appropriate for that type of stimulus. Or, as Kinsbourne (1970) has suggested, it may produce a perceptual orientation to the VF contralateral to the appropriate hemisphere. Unfortunately, it is not easy to devise ways to evaluate these alternatives, so the exact nature of the priming effect has not been well understood.

The present results bring some clarity to this issue. In this study, no asymmetries in the response to RVF and LVF probe stimuli or in CNV amplitude were found in the interval preceding the memory set when character type was cued. Hence, the role played by the latter two alternatives, viz., pre-exposural biases of visual attention and arousal, in mediating the asymmetric response to the memory set, may be discounted. Further, our finding that hemisheric asymmetries were present at approximately 180 ms following onset of the memory set on cue trials, but not in the interval preceding it, supports only the first alternative; namely, that the encoding processes engaged by Japanese and English character memory sets are asymmetrically represented and that these encoding processes must be set by the cue to operate efficiently. Consistent with this view, the relatively larger P2 evoked over the LH by English characters, and the relatively larger P2 evoked over the RH by Japanese characters, when character type was known, must be ascribed to the cue that forced the adoption of an encoding strategy at which one of the hemispheres was

more proficient and which was more efficiently applied to one character type than the other. Thus, English characters would be more readily encoded by the language dominant left hemisphere, and, Japanese characters, because they can be more efficiently encoded in a nonverbal manner, would be more readily encoded by the right hemisphere. Further evidence in support of this view is provided by the finding that the asymmetries observed in the memory set ERP were restricted to a component thought to index the encoding process, viz., P2 (cf., Chapman, McCrary, Bragdon, & Chapman, 1979; Chapman, McCrary, & Chapman, 1981).

One caveat should be stated: if it is indeed the case that the asymmetry in memory set ERP P2 amplitude on cue trials was due to the cue facilitating the adoption of an encoding strategy, which is asymmetrically represented, and which was appropriate to the verbal/nonverbal nature of the memory set, then one might have expected to find evidence for this in an hemispheric asymmetry of probe ERP P2 amplitude in the interval leading up to the memory set. In other words, one might have expected that the cueing x hemisphere x memory set character type interaction would be significant in this interval. There are no compelling explanations for why the probe ERP did not reflect this interaction. Of course, there is the ever-present possibility of a Type II error. Another possibility to be considered is the fact that the memory set and cue interval probe ERPs appear to reflect the activity of different brain regions, judging by their diffeent scalp topography. Some credence may be given to the former explanation by the finding that the cueing x hemisphere x memory set character type interaction was, in fact, only

marginally nonsignificant (p=0.083). Acceptance of this account awaits further study.

Although the results of the analysis of the memory set ERP imply, with some qualification, that encoding processes are asymmetrically represented, the analysis of probe ERPs elicited in the interval following the memory set suggests an asymmetric engagement of limited capacity short term memory processes. Figures 3.7 and 3.8b illustrate the magnitude of N2-P3 evoked by probe stimuli at each of three temporal positions in the memory interval. Note that at that moment in the trial when memory set size affected the amplitude of a memory interval probe ERP component (at the middle probe position; Figure 3.8b), and at which time we might therefore infer that the subject was most actively engaged in rehearsing the memory set, Japanese and English character memory loads differentially affected the response to RVF and LVF probe stimuli (Figure 3.7). That is, at this moment in the trial, retention of an English character memory set was associated with a smaller N2-P3 response to RVF than to LVF probes, whereas retention of a Japanese character memory set was associated with a smaller N2-P3 response to LVF than to RVF probes.

This finding supports our the hypothesis that verbal and nonverbal memory loads, by limiting available processing capacity, will selectively diminish the responsiveness of the left and right hemispheres, respectively, to task irrelevant visual stimulation. This finding also has several precedents in the literature (e.g., Papanicoulaou, Levin, Eisenberg, & Moore, 1983; Shucard, Cummins, Thomas, & Shucard, 1981; Shucard, Shucard, & Thomas, 1977).

The question of whether retrieval and comparison processes are also lateralized was answered by an analysis of the test (comparison) stimulus ERP. The results of this analysis showed that as set size increased, the amplitude of the N2 component elicited by the test stimulus increased over the right hemisphere on match trials, but showed no change on mismatch trials, or over the left hemisphere (Figure 3.5). While this interaction pattern is rather difficult to interpret (see Hellige, 1983, for a theoretical discussion of the interpretability of interaction patterns in laterality research), it can be construed, on its face, as supporting the view that the LH is more efficient than the RH in tasks requiring the serial comparison of input (the test stimulus) with previously stored information (Cohen, 1973; Hellige, 1980; O'Boyle & Hellige, 1982). An alternative explanation for the increase in N2 amplitude over the RH, as set size is increased, derives not from the load imposed by set size on a single cognitive process, but from the suggestion that as set size increases from one to two, or more, items, a qualitatively different memory comparison process may come onto play. Unfortunately, the present design does not allow the evaluation of the merits of these alternative accounts, since only two set sizes were used.

Quite apart from our findings of lateral asymmetries in the amplitudes of a number of ERP components, were a number of findings demonstrating the overall sensitivity of ERP measures to the varied demands placed on encoding, short term memory, and memory comparison processes. With regard to encoding and short term memory processes, the effects of manipulating difficulty were manifest in P3 amplitude, whereas with regard to the memory comparison process, the effect of

manipulating difficulty was manifest in both N2 and P3 amplitudes. Figure 3.8 juxtaposes plots of average P3 amplitudes elicited by the memory set and test stimuli, and average N2-P3 amplitudes elicited by memory interval probe stimuli, for each of the two set sizes. Note that for the memory set ERP (left panel), P3 amplitude was positively related to set size, whereas for the test stimulus ERP (right panel), and the probe ERP elicited at the middle position of the memory interval (center panel), an inverse relationship was found.

This complex relationship between set size and P3 amplitude has been demonstrated in study 1 of this series,. and results, perhaps, from the summative effects of two functionally independent (Squires, Squires, & Hillyard, 1975), but temporally overlapping cognitive processes, on P3 amplitude. The positive relationship between P3 amplitude and set size demonstrated in the memory set ERP probably reflects a graded mobilization of processing resources in direct proportion to the number of items which must be encoded from the memory set. This follows from the demonstration, in other contexts, that P3 amplitude increases as a positive function of the amount of information provided by the eliciting stimulus. Accordingly, infrequent stimuli have been shown to elicit larger P3's than frequent stimuli (Duncan-Johnson & Donchin, 1977), task relevant stimuli elicit larger P3's than task irrelevant stimuli (Courchesne, Hillyard, & Courchesne, 1977), and feedback stimuli elicit larger P3's than nonfeedback stimuli (Campbell, Courchesne, Picton, & Squires, 1979).

The negative relationship found between ERP P3 amplitudes and set size for both probe and test stimuli, has been demonstrated

repeatedly (Adam & Collins, 1978; Andreassi & Jusczak, 1984; Bauer, Goldstein, & Stern, 1986; Ford, Roth, Mohs, & Kopell, 1979; Gomer, Spicuzza, & O'Donnell, 1976; Kramer, Wickens, & Donchin, 1983; Kramer, Wickens, & Donchin, 1985) and has been attributed to a confounding of increased processing demands with reduced confidence. Accordingly, the reduction in probe ERP N2-P3 amplitude with increased memory loads in the memory interval could be ascribed to a reduction in the subject's confidence that he has encoded all of the items in the memory set. The reduction in the P3 elicited by the test stimulus (Table 6), as set size is increased, can also be ascribed to reduced confidence, although, in this instance, it is with regard to the decision as to whether the eliciting stimulus was a member of the memory set. Reduction in P3 amplitude as a function of the degree of uncertainty has also been demonstrated in a more direct manner (Squires, Hillyard, & Lindsay, 1973; Squires, Squires, & Hillyard, 1975).

With regard to the reaction time and error rate data, our findings agree with those of others (Hellige, 1980). The 45 ms processing time per item is in line with that in the literature and with RT in study 1. It is consistent also with the interpretation presented in study 2, that for the 6-item set there, the subjects encoded, on the average, fewer than the full set. This gave rise to the artifactually low estimate of processing rate. The additional exposure time allocated for stimulus intake in the present study, reduced the error rate somewhat for the 6-item set from that observed in study 2, and increased RT for the large set. This explanation also serves as an explanation for the presence of a set size effect in ERP

amplitude here and its absence in study 2.

The observed increase in reaction time with increasing set size on match trials, suggests the operation of a process by which the test stimulus is serially compared with the items comprising the memory set. The reliably longer RTs for mismatch items and the absence of a set size effect on mismatch RTs are best explained by the suggestion (Proctor, 1981) that correct mismatch and correct match judgments call upon qualitatively different processing modes.

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FIGURE CAPTIONS

Figure 3.1 Trial format

Figure 3.2 Representative examples of cue, memory set, and test stimulus ERPs (parietal derivation) recorded for small and large memory set size trials (Polarity = pos.up).

Figure 3.3 Representative examples of memory interval probe ERPs (parietal derivation) for small and large memory set size trials.

Figure 3.4 (A). Memory set ERP P2 amplitude (at parietal derivations) as a function of hemisphere and character type. In this and all subsequent figures, an asterisk indicates a statistically significant comparison.

(B). Memory set ERP P2 amplitude (at parietal derivations) as a function of hemisphere, character type, and cueing.

Figure 3.5 Test stimulus ERP N2 amplitude (at parietal derivations) as a function of character type, memory set size, and membership.

Figure 3.6 Probe ERP N1-P2 amplitude (at parietal derivations) as a function of hemisphere, visual field, and probe position. F-ratios are for tests of the hemisphere x visual field interaction at each probe position.

Figure 3.7 Probe ERP N2-P3 amplitude (at parietal derivations) as a function of hemisphere, visual field, and character type. F-ratios are for tests of the character type x visual field interaction at each probe position.

Figure 3.8 (A). Memory set ERP P3 amplitude (at temporal derivations) as a function of memory set size.

(B). Probe ERP N2-P3 amplitude (at temporal derivations) as a function of probe position and set size.

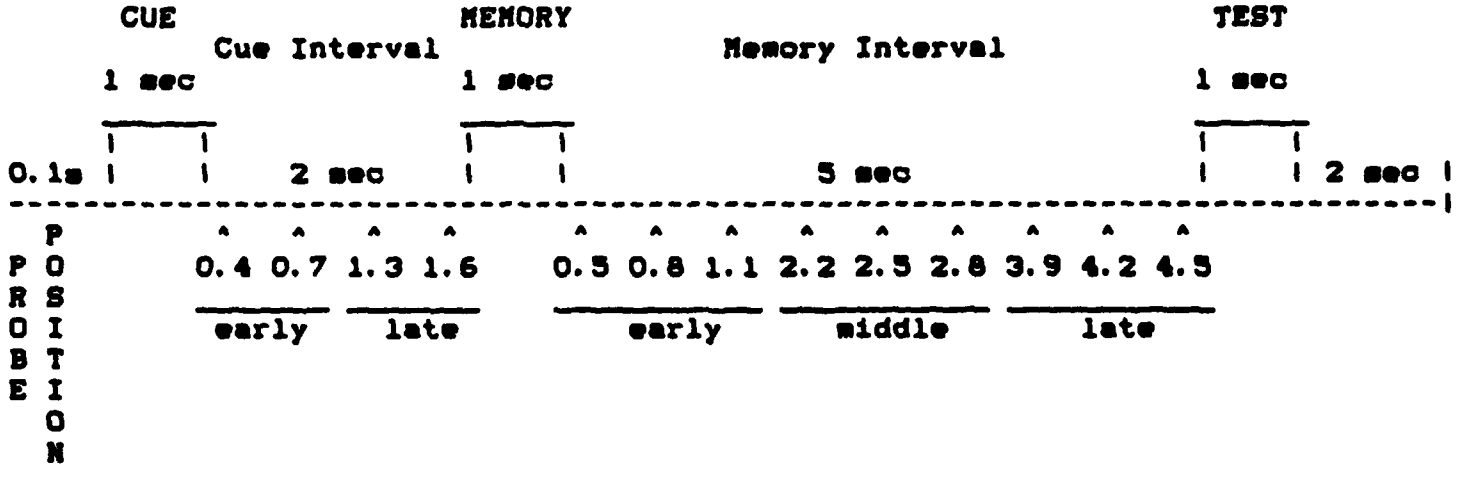
(C). Test stimulus ERP P3 amplitude (at temporal derivations) as a function of memory set size.

Figure 3.9 Probe ERP P1-N1 amplitude (at temporal derivations) as a function of visual field and hemisphere.

Figure 3.10 Probe ERP N1-P2 amplitude (at temporal derivations) as a function of visual field and character type.

Figure 3.11 Reaction time and error rate as a function of set size, character type, and membership.

Trial Format



N.B. Carrots designate the onset times (with respect to the offset of the preceding task stimulus) of probe stimuli.

Figure 3.1

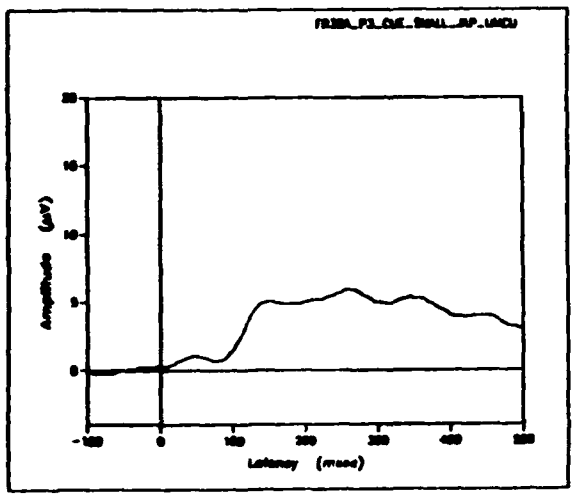
CUE STIMULUS ERP

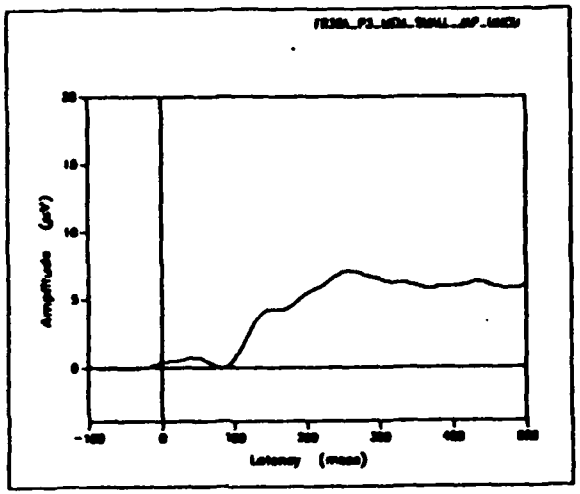
MEMORY SET ERP

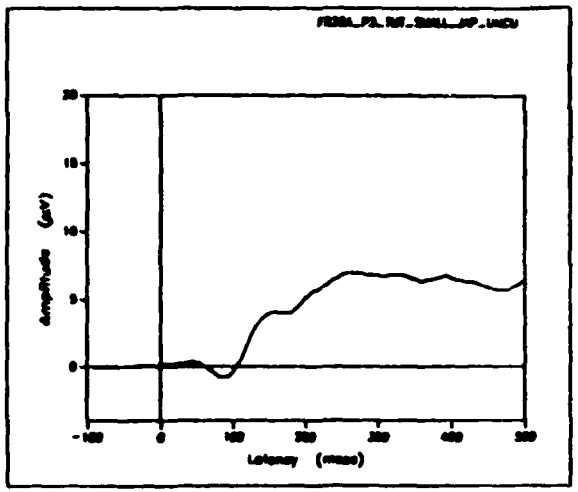
TEST STIMULUS ERP

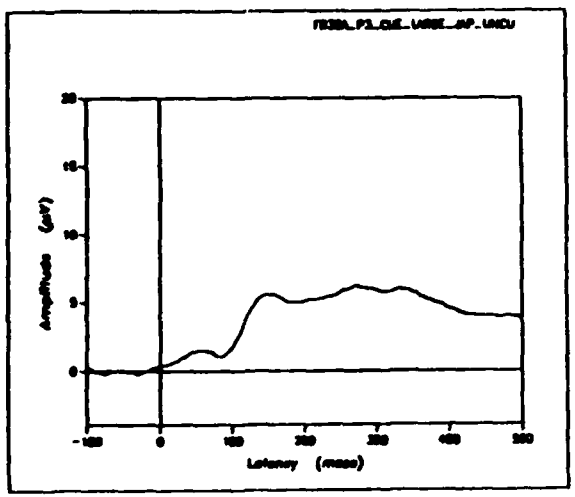
SMALL

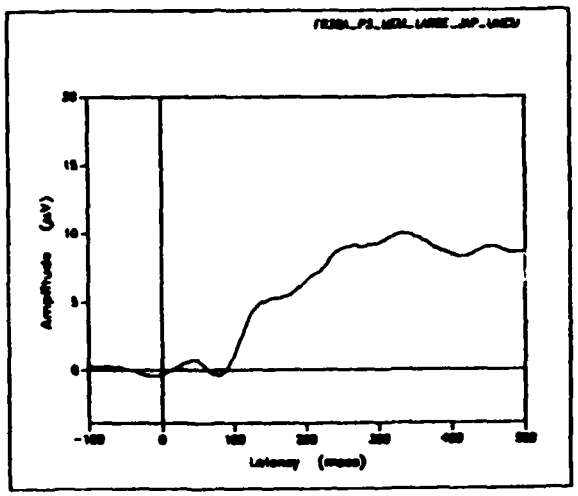
LARGE











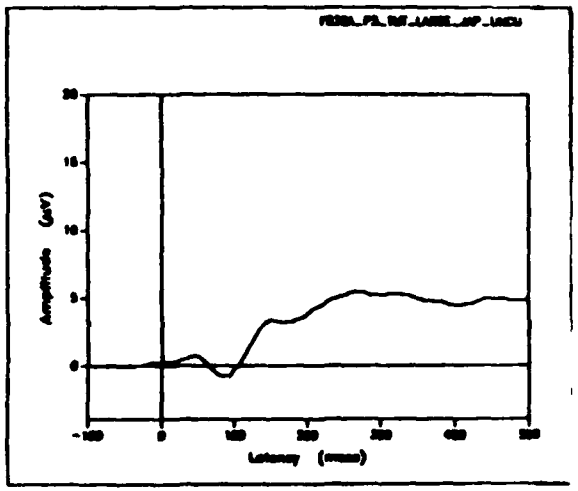


Figure 3.2

MEMORY INTERVAL PROBE ERPs

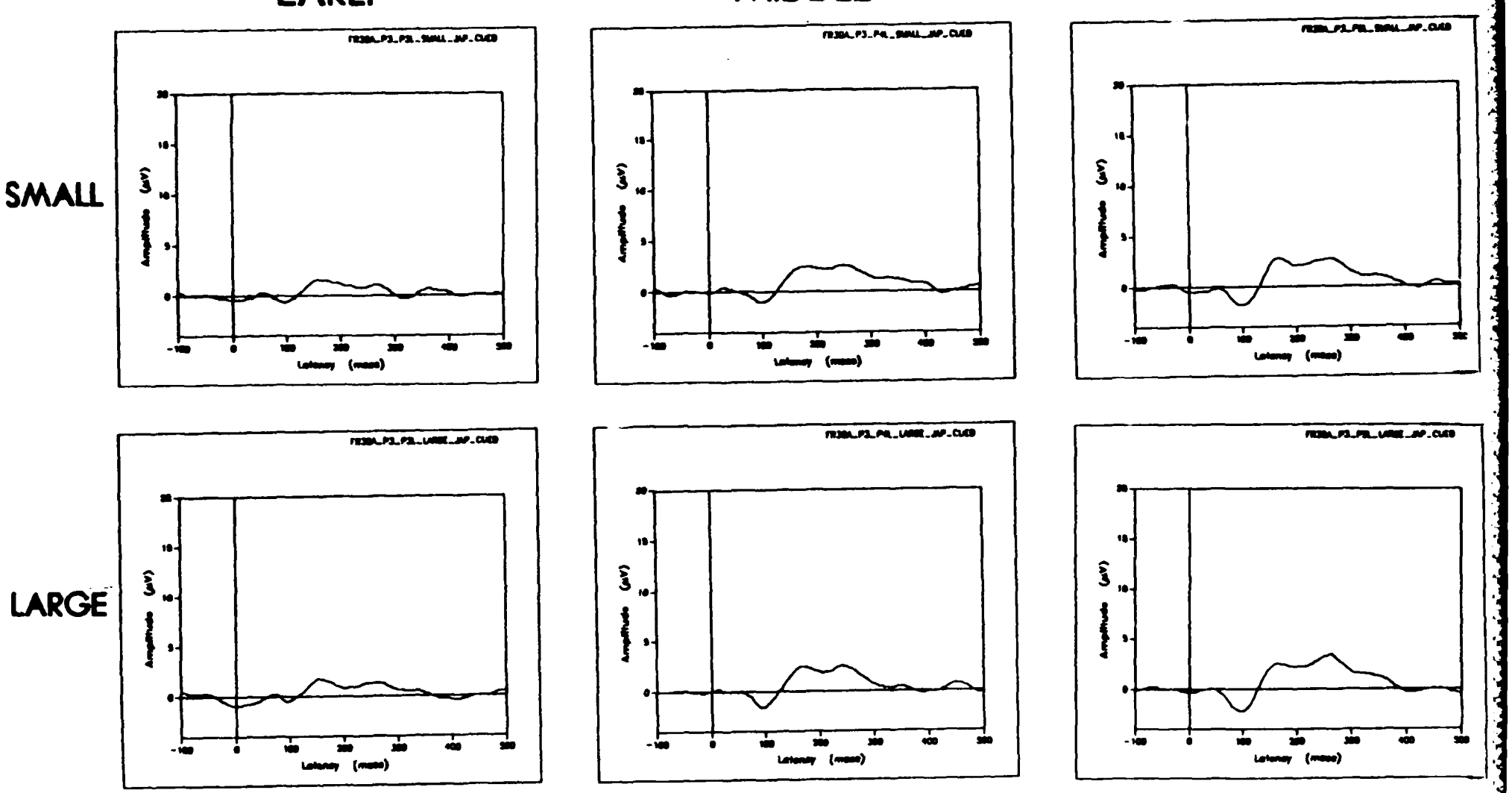
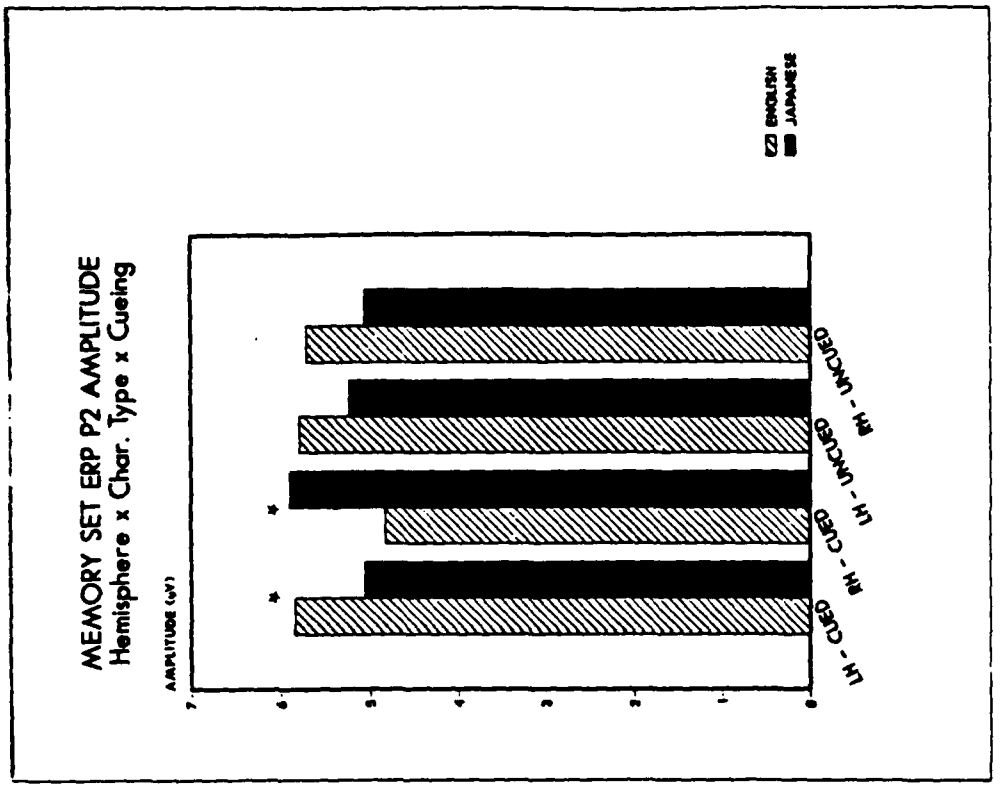


Figure 3.3


MEMORY SET ERP P2 AMPLITUDE
Hemisphere x Char. Type x Cueing
AMPLITUDE (uV)
ENGLISH
JAPANESE
LH - CUED
RH - CUED
LH - UNCUED
RH - UNCUED

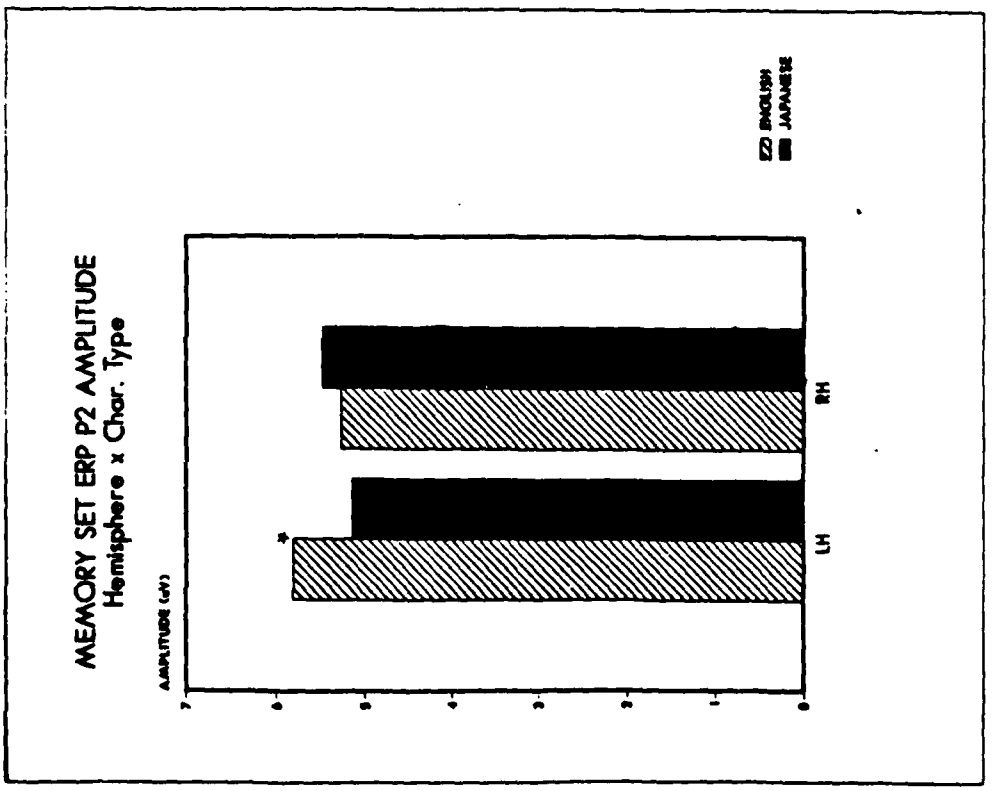
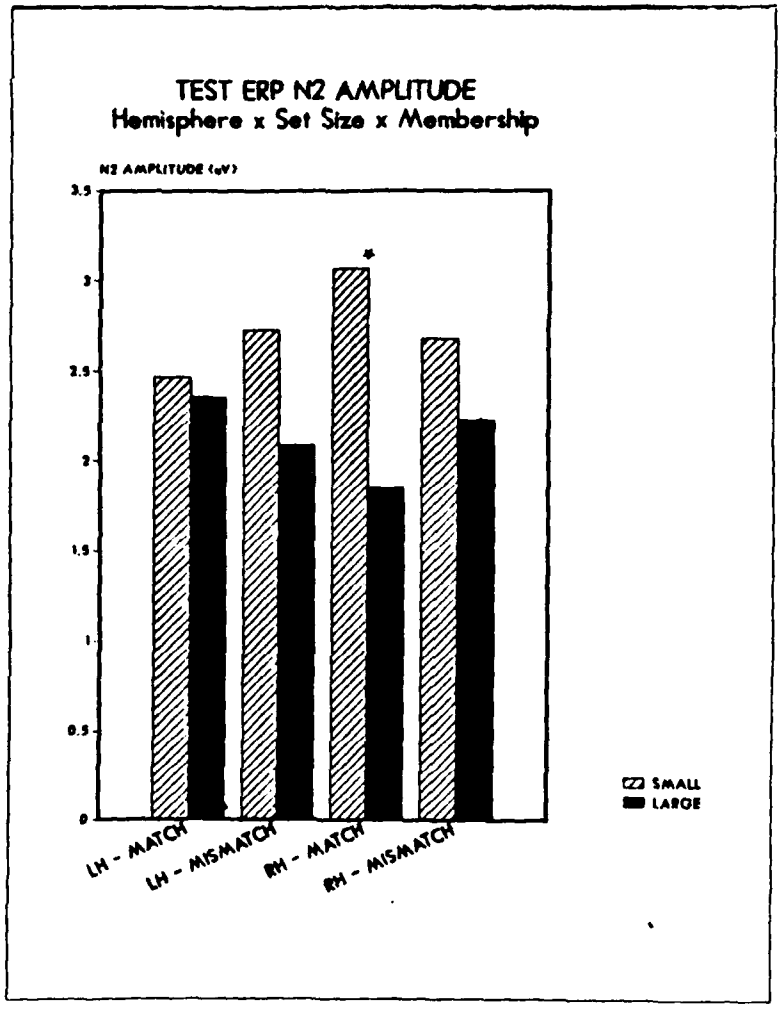
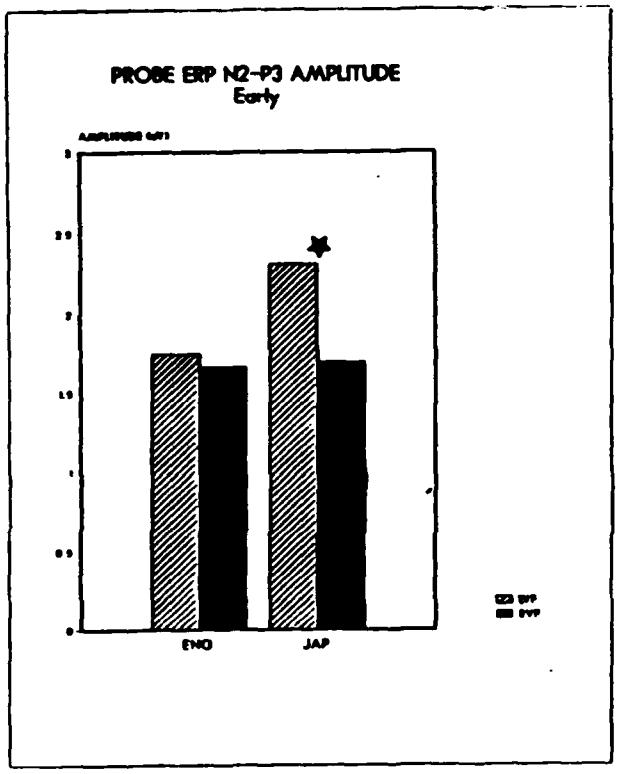

MEMORY SET ERP P2 AMPLITUDE
Hemisphere x Char. Type
AMPLITUDE (uV)
ENGLISH
JAPANESE
LH
RH

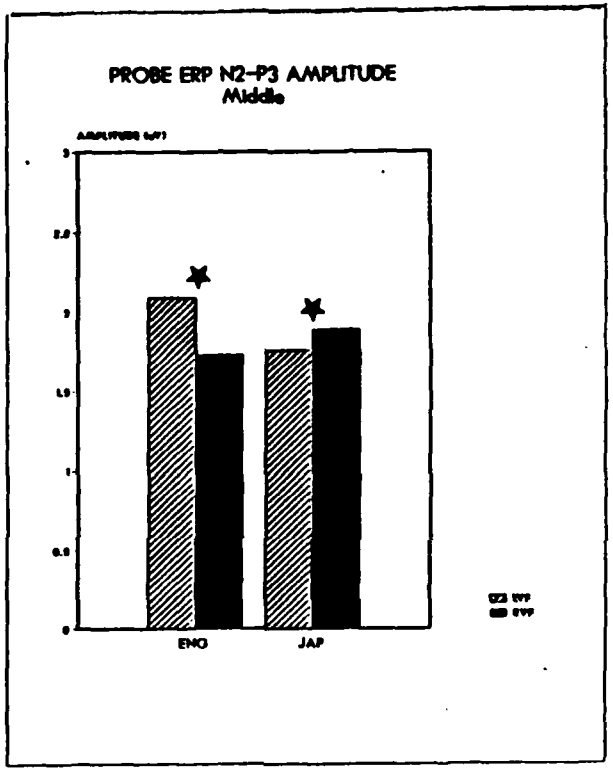
Figure 3.4

Figure 3.5

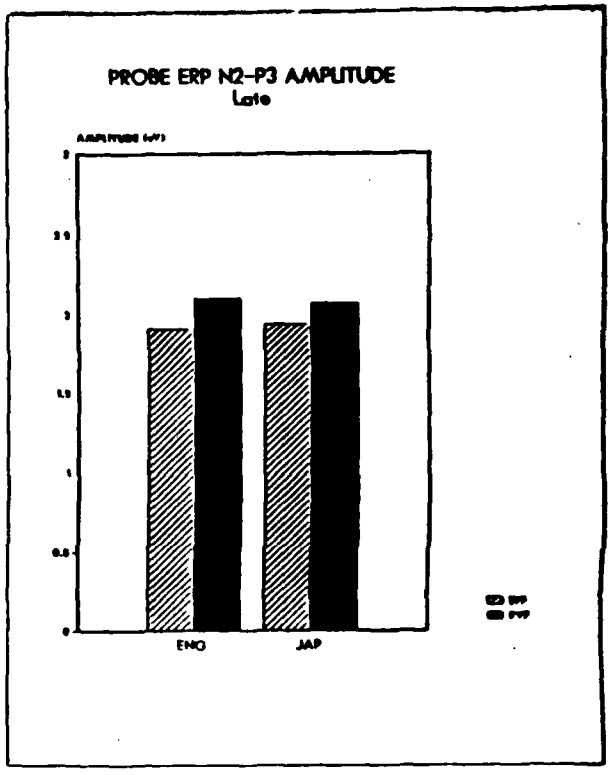

TEST ERP N2 AMPLITUDE
Hemisphere x Set Size x Membership
N2 AMPLITUDE (uV)
3.5
3
2.5
2
1.5
1
0.5
0
*
SMALL
LARGE
LH - MATCH
LH - MISMATCH
RH - MATCH
RH - MISMATCH



F(1, 12)=4.3

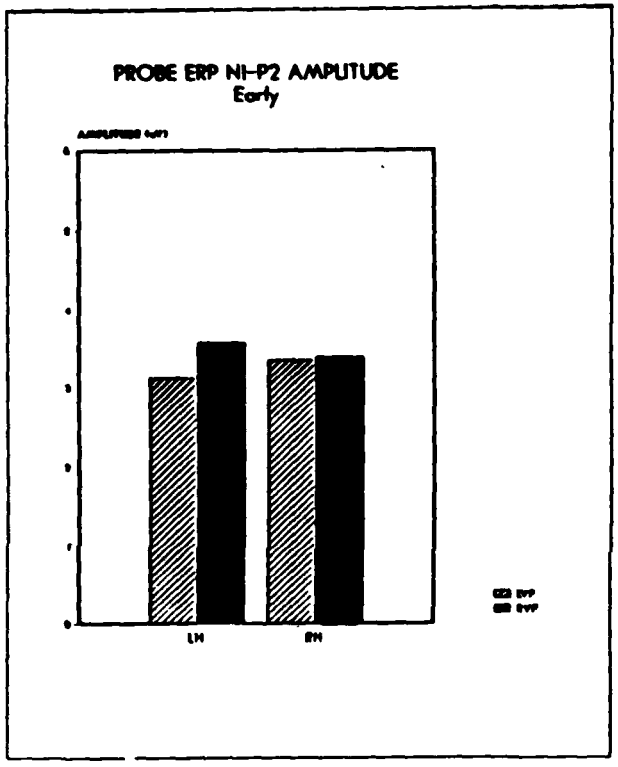


F(1, 12)=7.1*

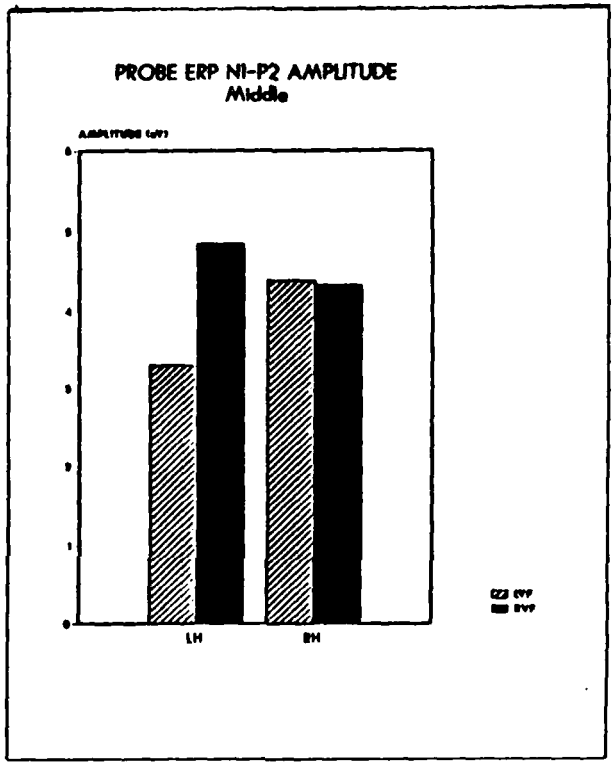


F(1, 12)=0.0

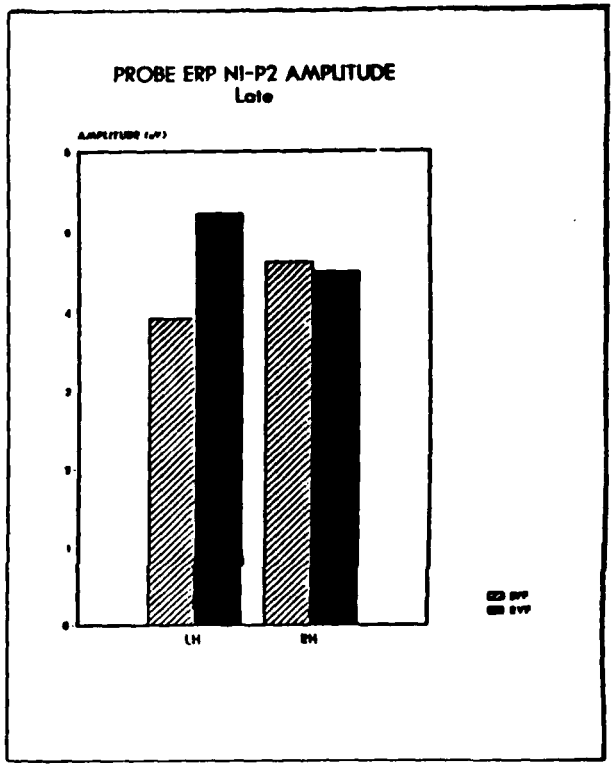
Figure 3.6



F(1, 12)=1.7

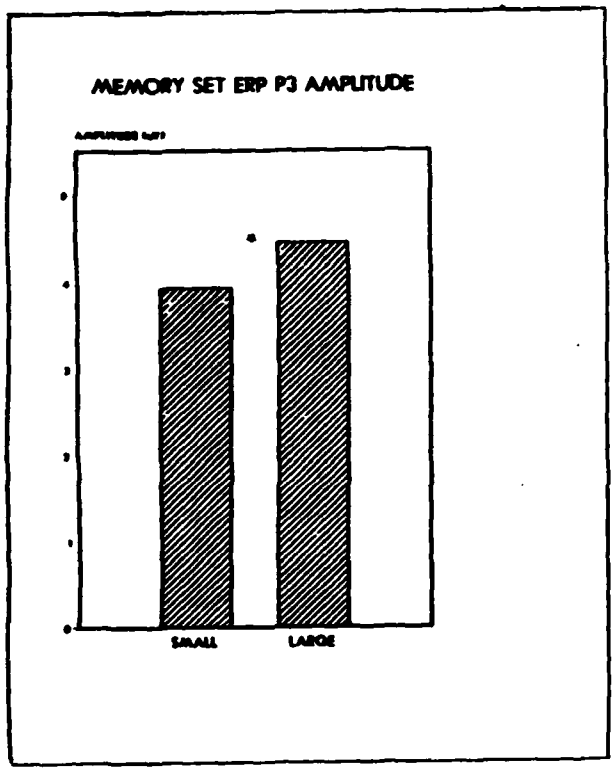


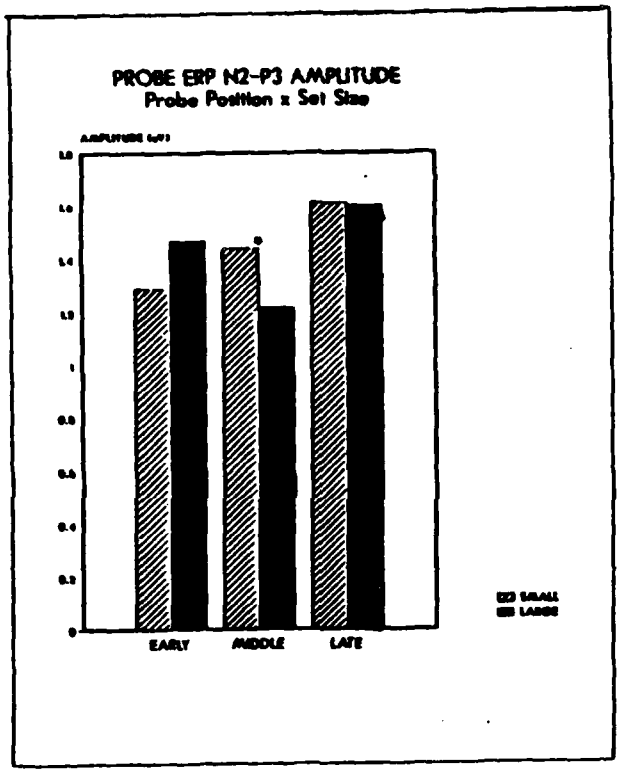
F(1, 12)=12.4*



F(1, 12)=6.9*

Figure 3.7


MEMORY SET ERP P3 AMPLITUDE
SMALL
LARGE


PROBE ERP N2-P3 AMPLITUDE
Probe Position x Set Size
EARLY
MIDDLE
LATE

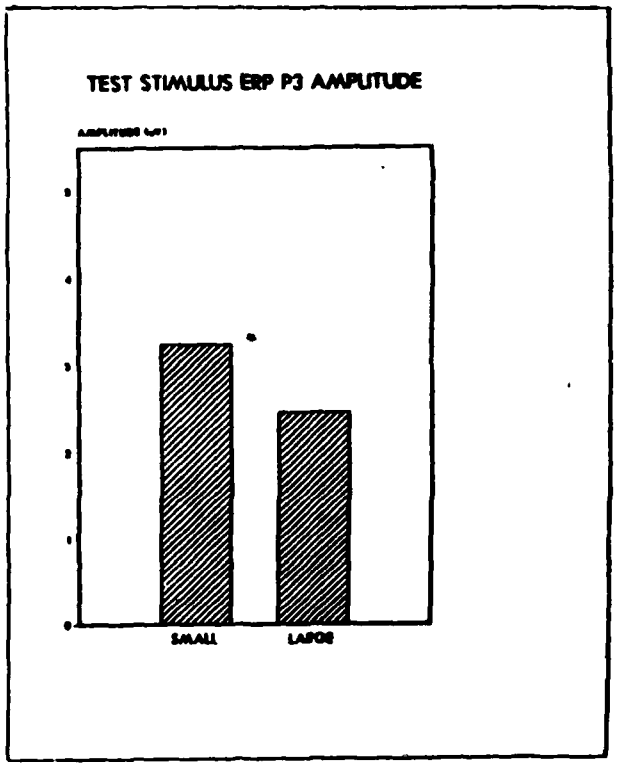

TEST STIMULUS ERP P3 AMPLITUDE
SMALL
LARGE

Figure 3.8

Figure 3.9

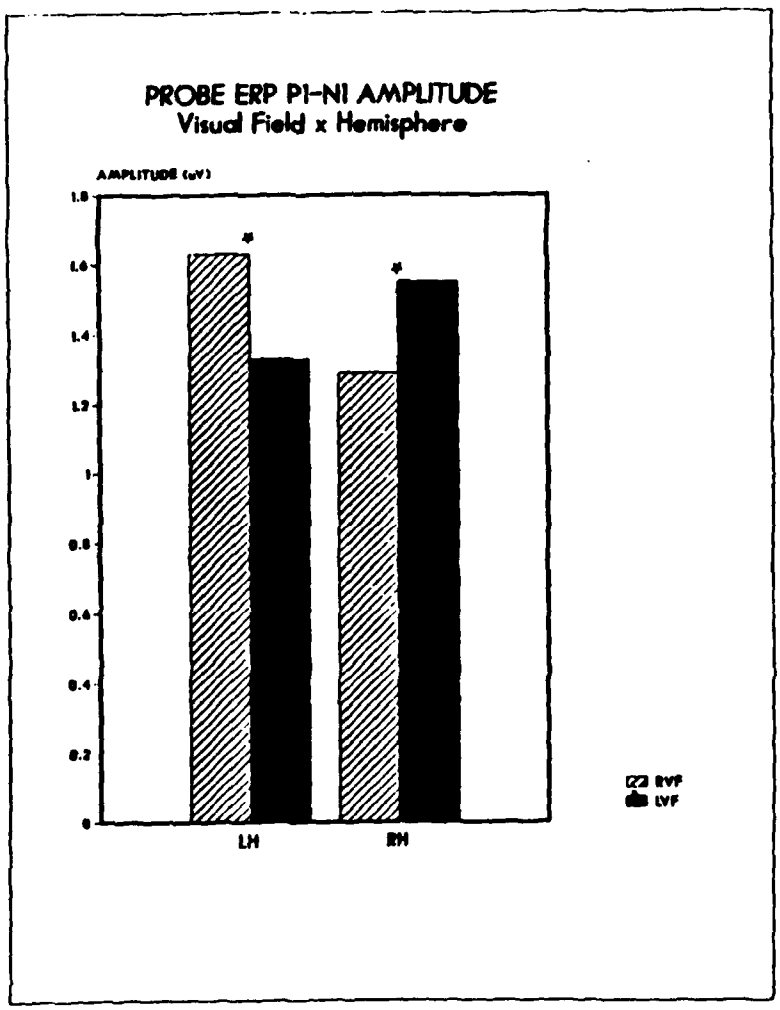
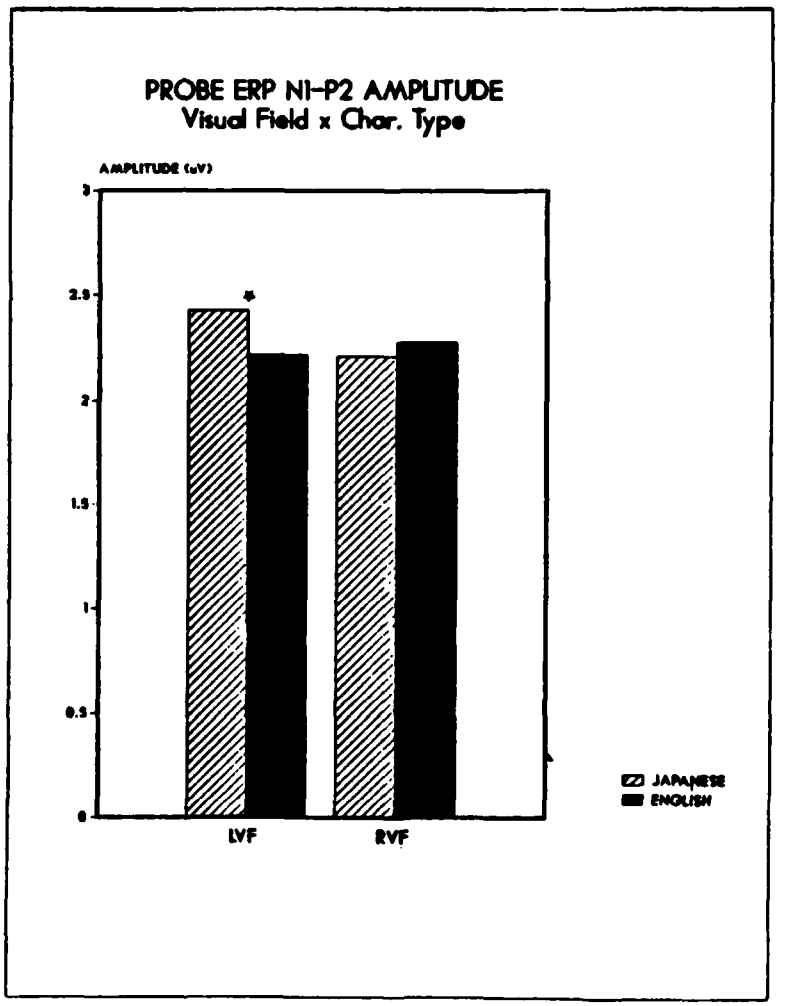
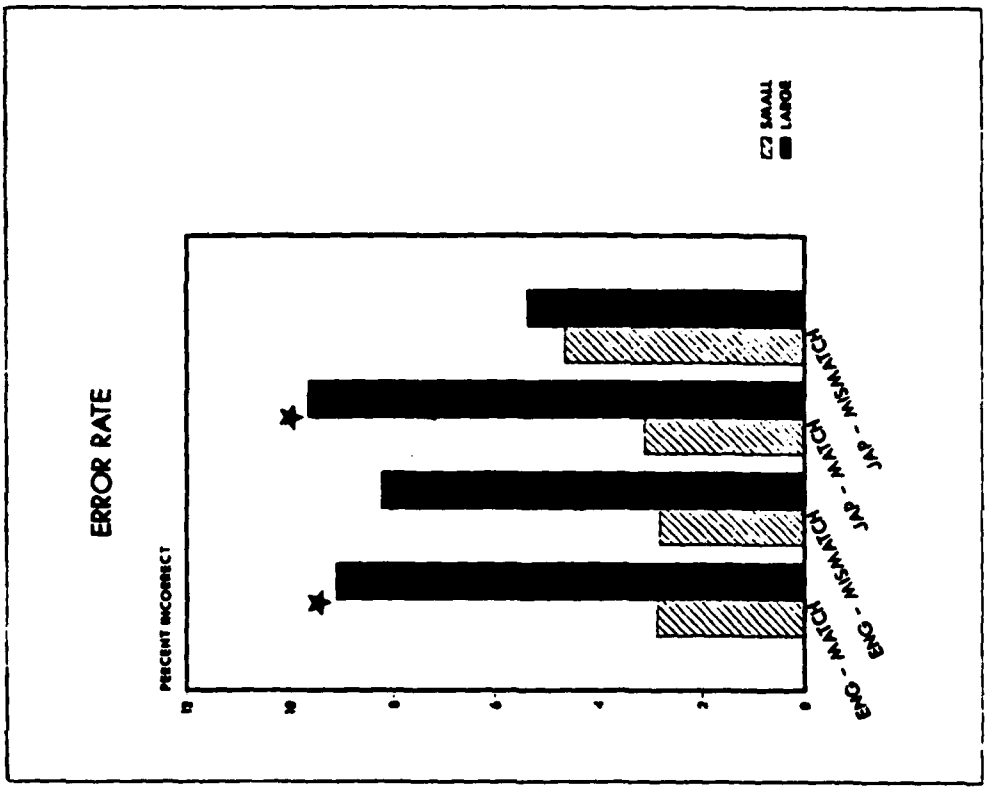

PROBE ERP P1-N1 AMPLITUDE
Visual Field x Hemisphere
AMPLITUDE (uV)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
*
*
LH
RH
RVF
LVF

Figure 3.10


PROBE ERP N1-P2 AMPLITUDE
Visual Field x Char. Type
AMPLITUDE (uV)
3
2.5
2
1.5
1
0.5
0
*
LVF
RVF
JAPANESE
ENGLISH


ERROR RATE
PERCENT INCORRECT
SMALL
LARGE
ENO - MATCH
ENO - MISMATCH
JAF - MATCH
JAF - MISMATCH

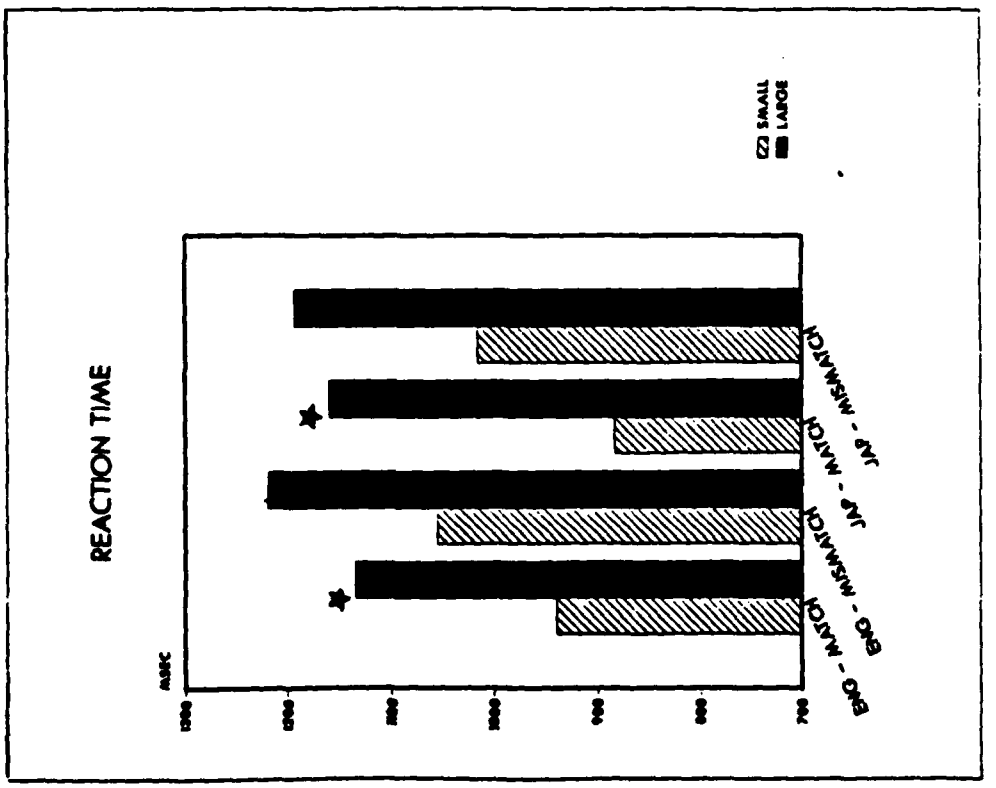

REACTION TIME
MSEC
SMALL
LARGE
ENO - MATCH
ENO - MISMATCH
JAF - MATCH
JAF - MISMATCH

Figure 3.11

END

10-86

DTIC